CENTRAL POWER SYSTEMS

ENSURING LOW-COST ELECTRIC POWER

Introduction

Program Areas

Innovations For Existing Plants

- Advanced NO_x Control
- $PM_{2.5}$ /Air Toxics Control
- Coal Combustion By-Products

Advanced Systems

- Low Emissions Boiler Systems
- Indirect Fired Cycles
- Pressurized Fluidized-Bed Combustion
- Gasification Technologies
- Advanced Turbine Systems
- Next Generation Turbines

The United States has a central electric power generation infrastructure unsurpassed in the world. It is an invaluable asset that affords U.S. industrial customers some of the lowest power rates in the world.

Innovations for Existing Plants

A major factor in realizing these low rates is the use of coal, our most abundant energy resource, for more than 50 percent of U.S. generating capacity.

Maintaining competitive energy rates and sustaining economic growth require that coal remains a mainstay in electric power generation. This requirement places importance on retaining existing coal-fired capacity and developing new capacity in the face of increased electric power demand and projected nuclear and hydroelectric plant retirements.

The challenge is that existing coal-fired plants must comply with increasingly stringent source emission and ambient air standards. For many of these plants, repowering rather than simply modifying the boilers may be necessary to meet environmental standards and remain competitive in a deregulated power market. There is a need to enhance the cost and performance of both environmental control retrofit and repowering technologies aimed at reducing emissions of sulfur dioxide (SO_2), oxides of nitrogen (NO_x), fine particulate matter (PM), mercury, and solid wastes.

New York State Electric & Gas Corporation's Milliken Station hosted a Clean Coal Technology Project to demonstrate high efficiency SO_2, NO_x, and particulate control without discharge of solid or liquid wastes

Advanced Systems

Coal

New coal-fired capacity faces even greater challenges, particularly with the implementation of utility restructuring. To maintain ambient air standards, new capacity additions will have to achieve near-zero pollutant emissions. Concerns over global climate change have placed a premium on efficiency and use of carbon-neutral renewable fuels. Solid waste disposal is becoming an increasingly difficult permitting issue. Moreover, under utility restructuring, power generators must shoulder the cost and risk of installing new capacity rather than the consumer. This fact makes the capital intensive, difficult to permit coal-fired plant somewhat less attractive. In addition, uncertainty associated with utility restructuring has impacted reliability of delivery. Power generators are increasing capacity factors on existing plants rather than adding capacity, which reduces reserve margins and improves system reliability.

The next generation of coal-fired power plants is emerging. These systems offer the potential to be competitive from a cost and performance standpoint with all other power systems. But, these plants must first undergo replication to reduce cost and optimize performance. This opportunity exists in foreign markets dependent on coal as a feedstock, such as developing Asia. China and India alone are projected to account for 33 percent of the total increase in world energy consumption over the next two decades. Opportunities exist for advanced coal-based systems offering superior environmental performance, fuel flexibility, and coproduction and cogeneration capabilities.

Natural Gas

Natural gas-based capacity is expected to provide the primary domestic response to new power demands over the next two decades. Ensuring conservation of this premium fuel resource requires increasingly efficient natural gas-powered systems.

The U.S. Energy Information Administration (EIA) projects that: (1) 300 gigawatts of new capacity will be needed to meet growing demand and to replace plant retirements; and (2) natural gas will fuel nearly 90 percent of the new capacity requirement. The reasons for the move to increased natural gas-based systems include the relatively low capital costs, short permitting and construction time, and superior environmental performance of gas turbines. The concern is the strain such demand might have on natural gas supplies and infrastructure. Strides toward enhancing the efficiency of natural gas-based power systems serve to protect U.S. reserves of this premium fuel and address global climate change concerns as well.

Vision 21

Ultimately, a new generation of Vision 21 technologies is needed to expand the fuel resource base to wastes and renewables, provide a multiplicity of high-value products in lieu of wastes, realize significant improvements in efficiency and emissions reduction, and facilitate CO_2 capture and sequestration.

Fuel flexibility is critical to enabling use of low-cost indigenous fuels, using wastes as fuel to address growing solid waste management problems, and incorporating renewable fuels to reduce greenhouse gas emissions. Highly efficient use of the fuels is important for reducing cost, lowering emissions, and facilitating carbon dioxide (CO_2) capture for sequestration. Product flexibility is needed to enhance efficiency, broaden market applications, produce vital chemicals or transportation fuels, and improve return on investment. Near-zero emissions are requisite to environmental acceptability.

Clean Coal Technology Program

The Clean Coal Technology (CCT) demonstration program supports both the Innovations for Existing Plants and Advanced Systems efforts under the Central Power Systems program. This \$5.2 billion cost-shared government/industry partnership addresses environmental concerns associated with coal use. Of the 38 active CCT projects, there are 29 projects, valued at \$3.5 billion, that address central systems applications — 18 environmental control projects and 11 advanced electric power generation projects. The other 9 projects involve coal processing for clean fuels and industrial applications, which are addressed in the Fuels section. All 18 environmental control projects have completed operation. Four of the 11 advanced electric power generation projects completed operations, two are in operation, and the balance are either in design or construction.

The CCT program will be discussed in this section in the context of contributions and accomplishments relative to Innovations for Existing Plants and Advanced Systems efforts.

DRIVERS

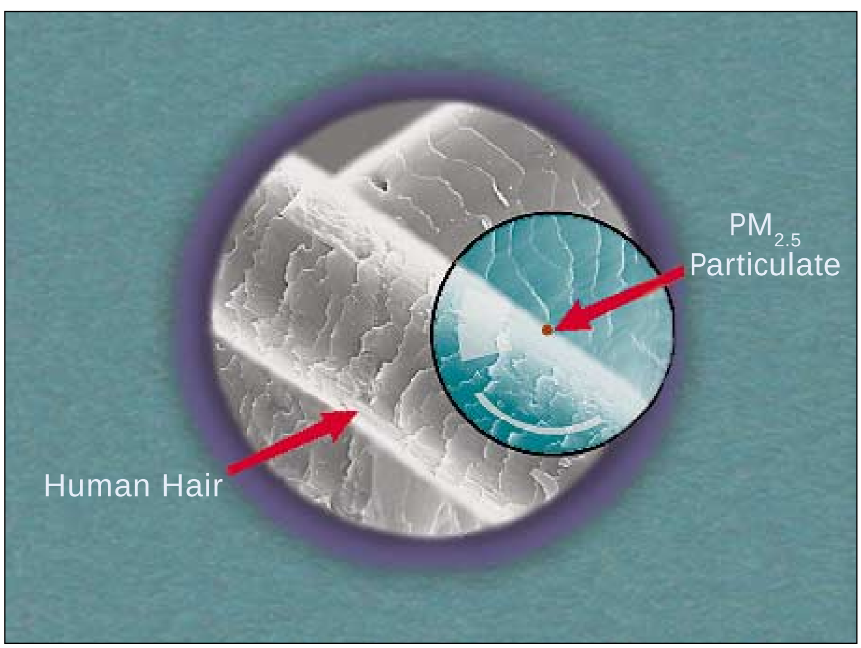
Title IV of the Clean Air Act Amendments of 1990 (CAAA) established source emissions standards for SO_2, NO_x, and particulate matter applicable to existing plants in two phases. The more stringent second phase came into effect in January 2000. Title IV requires Group 1 boilers, which represent 80 percent of the U.S. coal-fired boiler capacity, to meet NO_x emission levels of 0.40–0.46 lb/10^6 Btu, and Group 2 boilers to meet NO_x emission levels ranging from 0.68–0.86 lb/10^6 Btu. All existing boilers must meet SO_2 emission levels of 1.2 lb/10^6 Btu and a sliding scale reduction of 70–90 percent depending on the input fuel sulfur content. The resultant SO_2 emission levels are generally 0.3 lb/10^6 Btu for low-sulfur coals and 0.6 lb/10^6 Btu for high-sulfur coals. Furthermore, Title IV caps SO_2 emissions at 8.9 million tons per year beyond 2000 (as a reference, 1970 emission levels were 16 million tons). Over the coming years, as stockpiled SO_2 trading allowances expire and as coal use increases with economic growth, the cap on SO_2 emissions serves to further limit source emission rates.

Title III of the CAAA, Hazardous Air Pollutants (HAPs), requires the U.S. Environmental Protection Agency (EPA) to implement regulatory standards, if warranted, for 189 air toxics from sources emitting 25 tons annually of any combination of pollutants or 10 tons annually of a single pollutant. Mercury was specifically identified for study and possible regulation development. In December 2000, EPA decided to proceed with mercury regulation development. Proposed regulations are to be issued by December 2003 and final regulations are to be issued by December 2004.

Under Title I of the CAAA, EPA revised the National Ambient Air Quality Standards (NAAQS) in July 1997 to address ambient air concentrations of particulate matter (PM) in the respirable range of 2.5 micrometers (microns) in diameter or less ($PM_{2.5}$). Previous fine particulate standards dealt with airborne material in the inhalable dust range of 10 microns in diameter or less (PM_{10}). The $PM_{2.5}$ standard brings into play primary sources such as fly ash, carbon soot, and acid mists (aerosols), and secondary sources such as ammonium sulfates and nitrates from precursor SO_2 and NO_x gases. Monitoring to ascertain $PM_{2.5}$ attainment is ongoing, with designations of non-attainment expected by 2003–2004, and State Implementation Plans (SIPs) for compliance expected by 2007–2008, with compliance by 2013–2014. Some analysts project that an interim action to further reduce SO_2 may evolve in the form of a "SIP Call," which could call for substantial SO_2 reductions by 2006.

The Toxic Release Inventory (TRI) also has potential ramifications for $PM_{2.5}$ control. The TRI is a public database maintained by EPA on releases of toxic substances from various industries. Electric utilities began reporting for the first time under TRI in July 1999. Acid aerosols in the $PM_{2.5}$ size range, such as sulfuric acid, and trace element emissions are reported substances. While emission rates are quite low, the cumulative numbers appear significant and may precipitate further regulatory action.

Also under Title I, EPA revised the NAAQS in July 1997 for ozone. The ozone standards in turn impact NO_x emissions because NO_x is a precursor to ozone formation. As an interim measure, EPA issued a rulemaking in response to recommendations of a 37 state Ozone Transport Assessment Group



OVERVIEW

NETL $PM_{2.5}$ monitoring site

(OTAG). The rulemaking, in the form of a "SIP Call," requires 22 eastern states and the District of Columbia to reduce NO_x emissions by specified amounts (budgets) by May 2003. The expected emission limits for power plants is 0.15 lb/10^6 Btu, which generally requires relatively expensive selective catalytic reduction (SCR) technology. Under the general provisions of the ozone NAAQS provisions, revised SIPs are expected by 2003, with compliance ranging from 2003–2018 depending on the air quality in a particular area.

The EPA also proposed regional haze regulations in July 1997 focused on the impact of $PM_{2.5}$ on visibility impairment in Class I ("pristine") areas of the United States. However, there remain numerous uncertainties regarding linkage between coal-fired boiler emissions and the concentration and composition of ambient fine particulate matter. Moreover, the National Research Council (NRC) recently recommended that EPA place a high priority on better understanding the relationship between actual personal exposure to $PM_{2.5}$ and ambient concentrations measured at stationary outdoor monitors. The NRC also recommended greater chemical speciation of both emission sources and ambient $PM_{2.5}$ to improve understanding of biologically important components and characteristics of $PM_{2.5}$.

The Fiscal Year 1998 Congressional Appropriations called for DOE, through the National Energy Technology Laboratory (NETL), to build upon its existing $PM_{2.5}$ efforts toward addressing the issues of coal-based power generation contributions to ambient air degradation, and more specifically, the contribution of substances having known health and environmental effects. NETL is to add to the science of source-receptor relationships between power plants and public exposure to adverse airborne substances, and assess the impact of the new NAAQS provisions on coal-based power systems.

In April 2000, EPA formally concluded that coal combustion by-products (CCBs) — fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) by-products — do not warrant regulation as hazardous wastes. Barriers remain, however, as to the most effective management option for CCBs such as use in a variety of applications from road bed stabilization and cement supplements to value-added construction materials. Barriers include: (1) lack of liability exclusion for CCBs under the federal Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); (2) treatment of fly ash by most states as a solid waste through restrictive regulations; (3) lack of information on the availability, quality, and beneficial uses of CCBs supported by state and federal agencies; and (4) changes to CCB characteristics brought about by combustion modification for NO_x control. While these barriers persist, incentives for CCB use exist as well, including reduced CO_2 generation in cement processing through CCB substitution and declining landfill capacity and increasingly stringent disposal regulations.

ACCOMPLISHMENTS

The CCT program provided a portfolio of environmental control technologies enabling power generators to cost-effectively comply with Title IV of the CAAA for SO_2, NO_x, and particulate matter. The CCT projects redefined the state-of-the-art for sorbent-based scrubbers, nearly halving operating and capital costs, and producing valuable by-products instead of wastes. Lower cost sorbent injection and spray dryer options also emerged for space constrained, older and smaller plants. Also demonstrated were more sophisticated synergistic integrated control systems offering high SO_2, NO_x, and PM capture efficiency. Demonstrations completed the development of low-NO_x burners for all boiler types except cyclone boilers, making low-NO_x burners the centerpiece for Title IV NO_x compliance. Another combustion modification technique, reburning technology using both natural gas and coal, was also demonstrated to address cyclone boilers and serve as an adjunct to low-NO_x burners. Applicability and effectiveness of post-combustion SCR and selective non-catalytic reduction (SNCR) was evaluated as well.

The CCT program also provides the foundation for development of advanced NO_x controls to address requirements precipitated by Title I NAAQS provisions and possible additional reductions under future regulations. The projects produced a comprehensive database on the mechanisms for NO_x formation and mitigation. To supplement the database, further evaluations were carried out through collaborative R&D projects with industry. The R&D addressed such areas as advanced reburning, SNCR and SCR/SNCR hybrids, improved electrostatic precipitator (ESP) design, and ESP/baghouse hybrids.

Through both the CCT and R&D programs, DOE coordinated an effort with EPA and industry to characterize air toxics emissions from a representative sample of coal-fired power plants. The effort was instrumental in establishing that: (1) trace elements, except for mercury, stay with the solid combustion residues (bottom ash, fly ash, and FGD by-products), making control a function of particulate matter collection efficiency; (2) combustion modification via low-NO_x burners and reburning does not produce semi-volatile or volatile organic compounds (VOCs); and (3) mercury adopts a vapor phase and largely escapes capture by flue gas cleanup equipment (e.g., scrubbers and electrostatic precipitators). Air toxics emissions characterization data, collected under the effort coordinated by DOE/EPA/industry, became a critical factor in a report to Congress on HAPs, which served to guide future regulatory direction. The result was a focus on mercury and no direct action to regulate power plant trace element or VOC emissions.

In recent years DOE, through NETL, has taken the lead role in CCB utilization R&D. NETL was instrumental in preparing a 1994 DOE Report to Congress (RTC) entitled *Barriers to the Increased Utilization of Coal Combustion/Desulfurization By-Products by Government and Commercial Sectors*, as well as an update of the RTC in 1998. These documents have served as road maps for coal combustion by-product R&D. More recently, NETL joined with the National Mine Reclamation Center, headquartered at West Virginia University, to forge a consortium of state agencies and universities, the Combustion By-Products Recycling Consortium (CBRC), with a mission to increase overall CCB utilization by 10 percent.

Low NO_x burner installation at Gulf Power Company's Plant Hammond, Coosa, Georgia

ACTIVITIES

Under the Innovations for Existing Plants program area, there are three major technical activities: Advanced NO_x Control, $PM_{2.5}$/Air Toxics, and Coal Combustion By-Products.

Advanced NO_x Control. Advanced NO_x Control activities include two major thrusts: (1) retrofitable NO_x controls capable of meeting Title I CAAA provisions for ozone and $PM_{2.5}$ (Title I NO_x Control); and (2) advanced low-NO_x combustion technology capable of far exceeding Title I CAAA provisions in response to projected future tightening of source emission and ambient air requirements. The effort draws upon combustion modification and post-combustion NO_x control technology development pursued under the CCT Program, as well as follow-up assessments of particularly promising technologies.

$PM_{2.5}$/Air Toxics Control. There are three basic thrusts under the $PM_{2.5}$/Air Toxics Control activity: (1) $PM_{2.5}$ characterization analyses, (2) $PM_{2.5}$ control development, and (3) mercury control development. $PM_{2.5}$ characterization analyses combine ambient air monitoring and source emission characterization to establish source-receptor relationships and to better understand formation and transport mechanisms. $PM_{2.5}$ control development seeks to develop and evaluate technologies to cost-effectively control both primary and secondary $PM_{2.5}$. Mercury control development pursues technology options that either augment existing flue gas cleanup controls or provide stand-alone control.

All $PM_{2.5}$/Air Toxics Control activities support the goal of negligible primary and secondary $PM_{2.5}$ constituents from Vision 21 plants.

Coal Combustion By-Products (CCBs). The CCB activities follow industrial ecology principles of recycling, or utilizing in some other manner, all process effluents that would otherwise be regarded as waste streams. The activities include: (1) addressing identified barriers to widespread CCB use through application of science and technology, and technology transfer; and (2) addressing evolving CCB issues associated with application of advanced power generation and pollution control systems. The goal is to increase the CCB utilization rate from the current 30 percent to 50 percent by 2010.

DOE, EPRI, and Public Service Company of Colorado are evaluating carbon injection as a mercury control option on a 600-actual cubic feet per minute test rig located at Public Service of Colorado’s 350-MWe Comanche facility

OVERVIEW

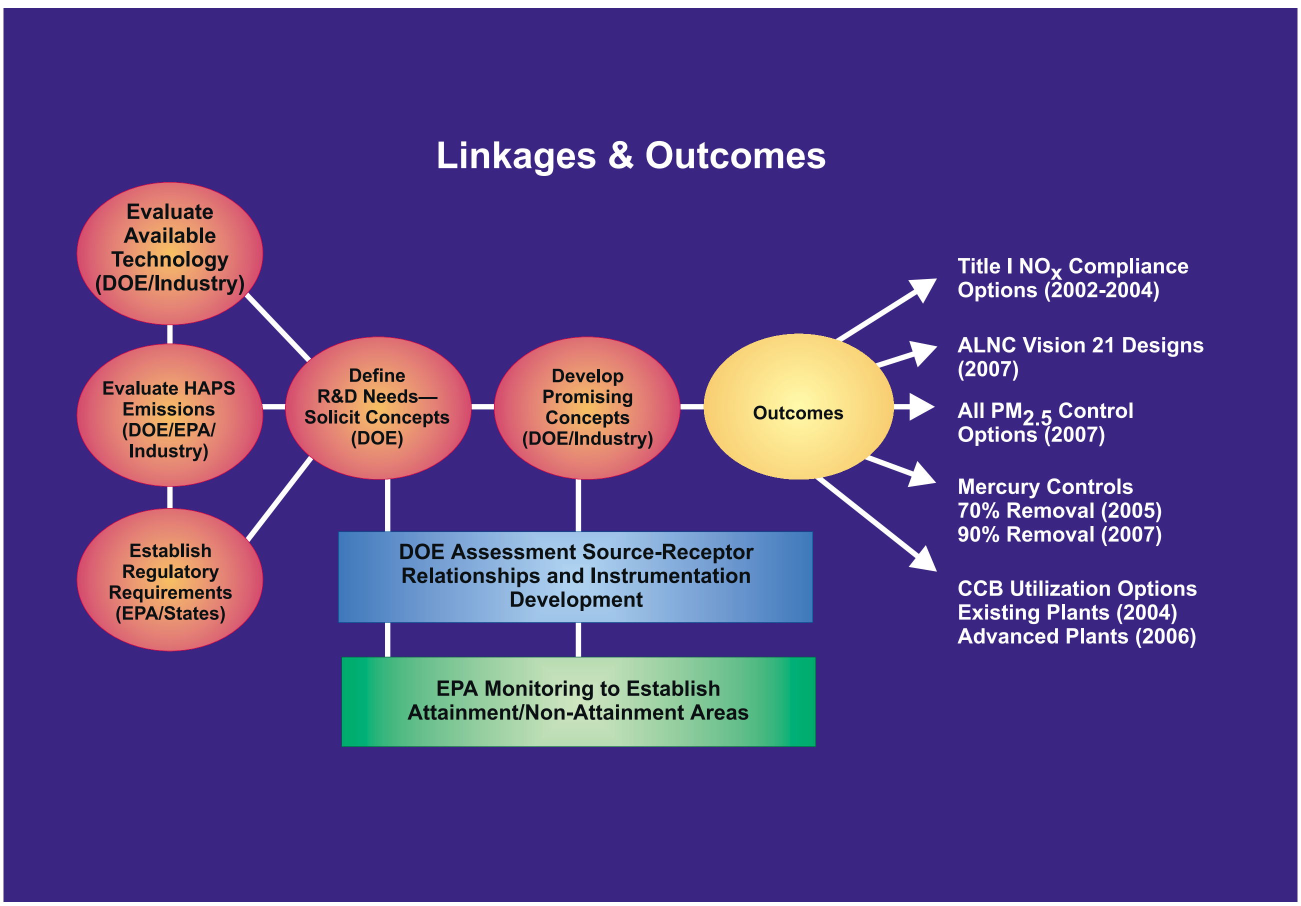
Links and Crosscuts

The exhibit below summarizes the basic steps taken, participants involved, and anticipated outcomes, along with parallel related activities in the Innovations for Existing Plants program area. Early activities supporting definition of technology needs include CCT projects and follow-on R&D projects to further explore promising technologies, the joint DOE/EPA/industry efforts to evaluate HAPs emissions at power plants, and extensive CCB characterization and utilization testing activities conducted largely through the Combustion By-Products Recycling Consortium (formerly the Emission Control By-Products Consortium). The Combustion By-products Recycling Consortium (CBRC) is overseen by NETL, structured on a regional basis, and carried out by state agencies and key universities.

DOE's approach to developing requisite environmental controls is issuance of a series of solicitations for promising concepts based on R&D needs analyses. Concept development draws on parallel national ambient air monitoring efforts.

DOE, through NETL, is participating in a national ambient air monitoring effort with EPA, local, and state environmental agencies, academia, and industry. EPA is establishing a national network of 1,500 $PM_{2.5}$ monitors to identify areas of attainment and non-attainment with the new $PM_{2.5}$ standard. DOE's role is to establish and operate several $PM_{2.5}$ "supersites" to provide increased temporal, chemical, phase, and size fraction resolution of $PM_{2.5}$ measurements.

DOE's monitoring effort is composed of four sites (two major and two supplemental) under the Upper Ohio River Valley Project, and five (one major and four supplemental) under the Steubenville Comprehensive Air Monitoring Project. The ambient air research station at NETL in South Park, Pennsylvania forms the third key component of the regional monitoring network. A fourth project, the Carnegie-Mellon University (CMU)/EPA Pittsburgh Supersite, was selected by DOE under a Fiscal Year 2000 broad-based solicitation.



Drivers

Providing new domestic generation capacity presents a major challenge both from an environmental and institutional standpoint. Overseas markets represent a major economic incentive and the opportunity to significantly reduce the projected growth in global greenhouse gas emissions for decades to come.

New capacity must vie with existing capacity in areas struggling to comply with the cap on SO_2 emissions and new ambient air standards for ozone and $PM_{2.5}$. Moreover, with available landfill capacity declining, solid waste management becomes an increasingly serious issue.

Both global climate change and pollutant emission concerns provide impetus for major improvements in efficiency, which enables less fuel use for a given quantity of energy. Public policy reflecting global climate change concerns promotes use of carbon-neutral fuels through mechanisms such as Renewable Portfolio Standards, which require a certain percentage of power generation capacity to be from renewable sources. Ultimately, carbon sequestration may be required to satisfy global climate change concerns. A key aspect of carbon sequestration is capture of carbon dioxide from the power generation system, which is facilitated by concentrating the carbon dioxide in the process of converting fuel to energy.

Under utility restructuring, the power generator, not the ratepayer, assumes the cost and risk of installing new capacity. Technology characteristics sought in this regime are low capital cost, rapid installation, and reliable performance. Uncertainty in the restructured utility market has resulted in limited investment in new capacity, as power generators await further definition of the rules of engagement under utility restructuring. The lack of new capacity coupled with retirements of a significant amount of nuclear capacity has severely reduced reserve margins in much of the country. The result has been an increasing number of power disruptions and occasions of reduced power quality as generators attempt to meet growing demand by increasing capacity factors on an aging fleet of power plants. These occurrences, along with a growing customer base requiring high-quality power for computer-based systems and sensitive electronic components, have escalated customer concern for reliability.

New capacity is needed to effectively power our economy

The projected reliance on natural gas to provide nearly 90 percent of new domestic electric power over the next two decades places a premium on efficiency to reduce operating costs by using less fuel and dampening demand-induced price increases. Strategic benefits include ensuring adequate reserves of this clean fuel for the foreseeable future.

World energy consumption is projected to increase by 60 percent between 1997 and 2020. More than one-half of the world's total projected increase in energy consumption is to come from coal-dependent Asia and natural gas-dependent Central and South America. Capturing a significant portion of these enormous markets with advanced U.S. power generation systems would not only boost the economy but impact greatly on global carbon emissions for the foreseeable future.

Accomplishments

The CCT program was instrumental in the commercial deployment of atmospheric fluidized-bed combustion (AFBC) by providing needed databases and commercial-scale demonstration. The AFBC technology offers tremendous fuel flexibility and provides SO_2 and NO_x control without the efficiency penalties of add-on equipment. There are nearly 10 gigawatts of installed utility-scale AFBC capacity worldwide.

Pressurized fluidized-bed combustion (PFBC) technology, designed to build on AFBC performance, also progressed under the CCT program. Demonstration at a major utility led to a first-generation PFBC commercial design, offering 40 percent efficiency and the beginning of market penetration. Sales include several 80-MWe units throughout Europe and a 360-MWe unit in Japan. The CCT program also provided the foundation for follow-on work designed to realize the full potential of PFBC.

Four CCT program integrated gasification combined-cycle (IGCC) demonstration projects, representing a diversity of gasifier types and cleanup systems, are pioneering the introduction of this technology by evaluating the systems in commercial service. As with PFBC, these early IGCC units are roughly 40 percent efficient. IGCC is realizing commercial sales, with an estimated 5 gigawatts of installed capacity expected by 2003. The CCT projects are serving to reduce risk for commercial sales and to provide a foundation for gasification systems development.

The DOE Advanced Turbine Systems (ATS) program has produced the most advanced combustion turbines in the world, incorporating breakthroughs that were barely imagined a decade ago. Two sizes of turbines emerged commercially through the ATS program — industrial-scale products less than 20 MW, and large, combined-cycle utility-scale products greater than 400 MW. Developers surpassed the original aggressive goals of the program. Achievements include increased fuel-to-electricity efficiency from about 50 percent to 60 percent for utility-scale gas turbines, and reduced NO_x emissions to single digits (9 ppm or less). Advances in the underlying science and technology have enabled pursuit of a next generation of turbine systems targeting intermediate capacity and further cost and performance improvements.

Tampa Electric Company's 250-MWe IGCC Polk Power Station

COMBUSTION SYSTEMS ACTIVITIES

Under the Advanced Systems program for Combustion Systems, there are three major technical activities: Low Emission Boiler Systems, Indirect Fired Cycles, and Pressurized Fluidized-Bed Combustion.

Low Emission Boiler Systems (LEBS). LEBS is an advanced pulverized coal-fired (PCF) system that takes pulverized coal-firing, the proven standard in coal-fired power generation, to new levels of performance. LEBS draws upon extensive design databases established for PCF systems over decades of service, developed for environmental controls under the CCT program, and evolved for supercritical steam cycles through hundreds of applications. Improved performance is realized by integrating environmental controls and a supercritical steam cycle into a PCF plant design.

A LEBS design by D.B. Riley emerged from nearly a decade of competitive evaluation of three designs. Evaluation included component and subsystem testing and research into high-temperature materials and advanced cycles, such as use of an ammonia-based "Kalina" cycle in lieu of steam. The D.B. Riley design incorporates an innovative low-NO_x U-fired slagging furnace, a regenerative moving-bed copper-oxide process for SO_2 and NO_x control, and a supercritical steam cycle. The design target is 42 percent efficiency and a 10 percent reduction in the cost of electricity.

These technologies and high-temperature materials developments supporting supercritical steam cycle advancement will become base technologies for Vision 21 combustion systems.

Indirect Fired Cycles (IFC). The IFC efforts are focused on concepts that support Vision 21 goals emerging from competitive development of High Performance Power Systems (HIPPS). The HIPPS designs transfer the heat of combustion to a cleaner working medium (air), which in turn drives an expansion turbine to generate electricity. Separating the combustion gases from the turbine avoids: (1) the temperature limitations imposed by flue gas cleanup technologies; (2) the need for extensive purification of the flue gas; and (3) exotic turbine blade metallurgy to avoid corrosion. Central to HIPPS and Vision 21 hybrids is a high-temperature air furnace to transfer the heat of combustion to the air working media. Also important is the development of a coal pyrolysis system to convert coal into a fuel gas, and development of a fuel gas cleanup system. Pyrolysis and fuel gas cleanup provide highly effective means of controlling pollutant emissions on the combustion side of the process. IFC designs emerging from the HIPPS effort are targeting efficiencies of 55 percent.

Pressurized Fluidized-Bed Combustion (PFBC). PFBC systems apply fluidized-bed combustion in a pressurized atmosphere to generate sufficient flue gas energy to drive a gas turbine and generate steam from the exhaust to drive a steam turbine. This combination, termed "combined-cycle," affords significantly higher efficiency than conventional single cycle combustion systems. Early efforts in the CCT program resulted in demonstration and commercialization of a first-generation PFBC, which simply uses the energy derived in the PFBC boiler to drive the gas turbine, and uses cyclone separators for particulate removal. Current activities are focused on development of a second generation PFBC that increases efficiency by integrating a coal pyrolysis unit (carbonizer) to produce a syngas for combustion in the gas turbine. This topping combustion addition provides more energy to the more efficient element of the combined-cycle — the gas turbine.

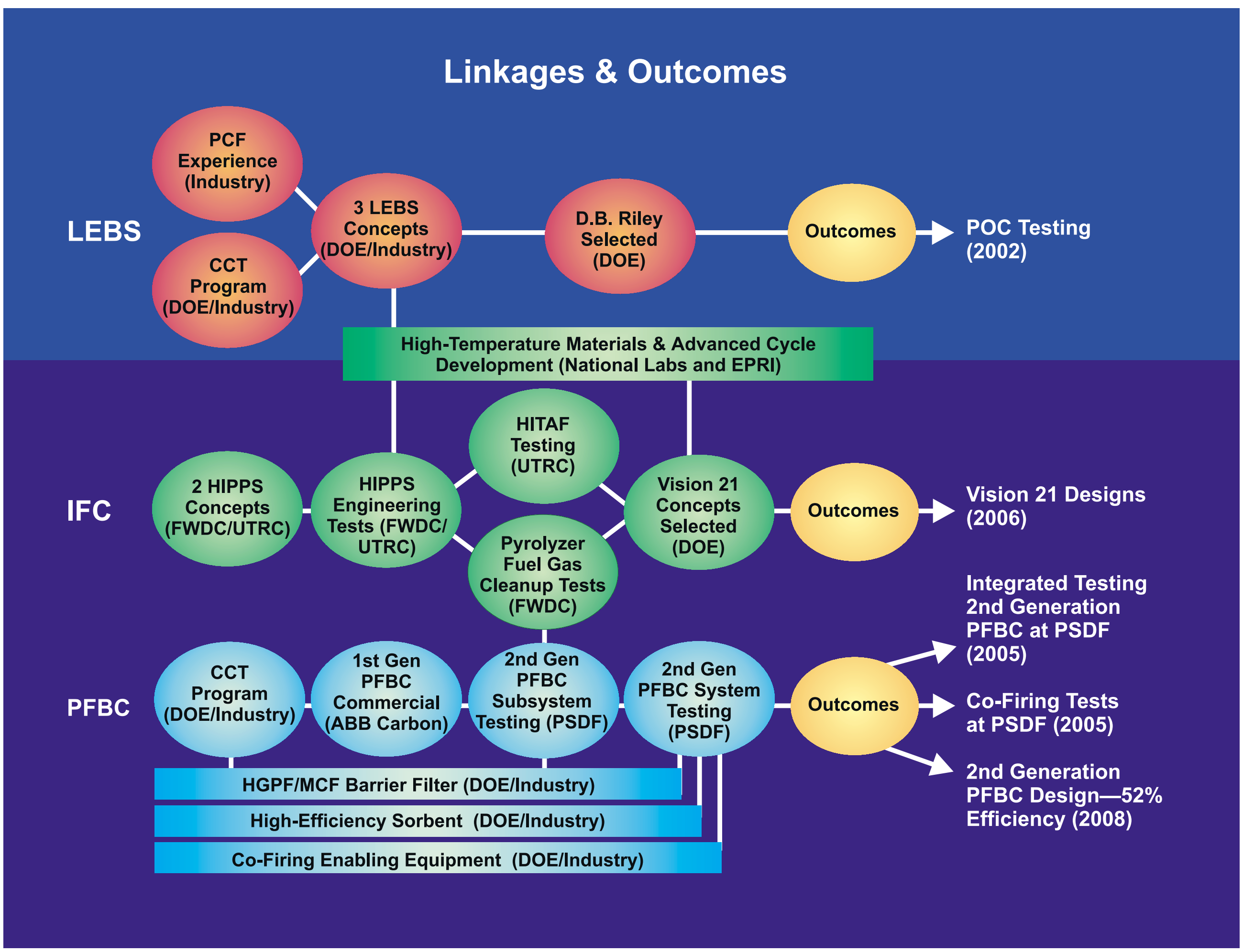
Realizing the potential of a second-generation PFBC requires development of several critical components. Hot gas particulate filtration (HGPF) and multi-contaminant filter (MCF) systems capable of operating at combustor and gasifier exit gas temperatures (1,200 °F–1,700 °F) are needed to enable use of high-efficiency gas turbines, and an efficient low-NO_x burner is needed to combust the syngas. To further leverage PFBC and address future environmental concerns, parallel efforts are ongoing to: develop more efficient sorbents to reduce operating costs and CO_2 emissions; pursue cofiring of carbon neutral fuels (biomass, forestry and agricultural wastes); ensure effective control of HAPs; and conduct systems studies on integrating supercritical steam and fuel cell cycles.

LINKS AND CROSSCUTS

The exhibit below summarizes the linkages and outcomes in Combustion Systems. LEBS evolved from industry experience with PCF and efforts in advanced environmental controls under the CCT program. Cost-shared cooperative agreements were awarded to three industry teams to develop LEBS concepts. Subsequent testing led to selection of a D.B. Riley LEBS design for Proof-of-Concept (POC) testing.

IFC efforts are focused on concepts emerging from HIPPS, which resulted from competitively selected awards of cost-shared cooperative agreements to two industry teams. Engineering tests have led to further development of key components needed to support Vision 21 goals — HITAF, coal pyrolysis, and pyrolysis fuel gas cleanup. Key components will be incorporated into Visions 21 plant concepts. Testing of the pyrolysis unit and pyrolysis fuel gas cleanup system may take place at the Power Systems Development Facility (PSDF) in conjunction with PFBC development activities.

PFBC efforts are directed primarily at development of a second-generation system, drawing heavily upon first-generation experience gained through the CCT program. Both PFBC system and component testing will take place largely at the PSDF, which is operated under a cost-shared agreement with Southern Company Services, Inc. Southern Company Services operates the facility in Wilsonville, Alabama for industry participants who fund 20 percent of the projects. DOE funds the balance and NETL oversees the activities. Component development activities critical to achievement of a second-generation PFBC are combined HGPF/MCF barrier filters, alternate high-efficiency sorbents, and equipment to enable co-firing, which are conducted primarily under cost-shared cooperative agreements.



GASIFICATION TECHNOLOGIES ACTIVITIES

Under the Gasification Technologies program, there are two key elements: Gasification Systems Technology, and System Engineering/Product Integration. Gasification Systems Technology has four major technical activities: (1) Advanced Gasification; (2) Gas Cleaning and Conditioning; (3) Gas Separation; and (4) Products/By-Products Utilization. The System Engineering/Product Integration activity provides updated analyses of gasification-based processes, identifies impediments to commercial deployment, and develops R&D performance targets.

Gasification technologies offer tremendous potential by converting hydrocarbon feedstocks into clean fuels, chemicals, and other saleable by-products. Essentially, no waste streams need result from gasification processes. Gas derived from gasification can produce nearly pollutant-free power and co-produce clean fuels and chemicals, if desired. Gasification used in an IGCC application has near-term potential for greater than 50 percent efficiency, and when applied in combination with fuel cells has the potential for greater than 60 percent efficiency.

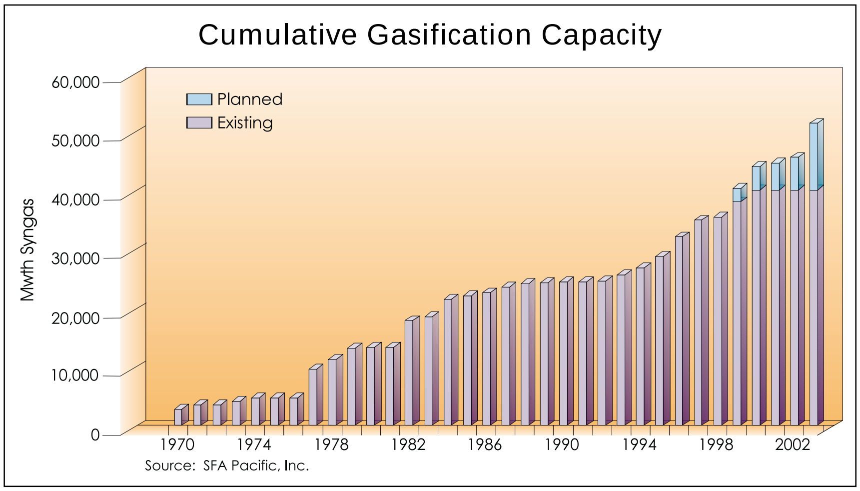
Gasification Systems Technology

Advanced Gasification. The Advanced Gasification activities focus on the development of a novel transport gasifier through an integrated program involving the University of North Dakota Energy and Environmental Research Center (UNDEERC), the PSDF, and NETL. Efforts also are directed at developing technologies for co-feeding coal and alternative feedstocks to high pressure gasifiers, the development of advanced materials, instrumentation, and controls; and exploring novel advanced gasifier concepts for application to Vision 21 systems.

Gas Cleaning and Conditioning. The Gas Cleaning and Conditioning area focuses on both hot gas and novel gas cleanup technologies that support Vision 21 goals by providing the gas quality needed for integration with fuel cells, advanced turbines, and synthesis gas conversion technologies. Work will continue on the development of high-temperature, attrition resistant regenerable sorbents and reactor models for the transport desulfurization reactor, particulate filters, and novel cleaning approaches operating at temperatures above 540 °C to meet near-zero emission requirements.

Gas Separation. Gas Separation activities primarily support Vision 21 by developing technologies for hydrogen separation and air separation, and developing concepts for carbon dioxide mitigation, separation, and utilization.

Products/By-Products. The Products/By-Products element focuses on the development and utilization of process and waste streams to generate value-added marketable products and to minimize waste disposal. New approaches for recovering the sulfur from process waste streams will be explored and a strategy will be developed and implemented to explore new products and markets for gasifier ash and slag, particularly from co-feed operations.



System Engineering/ Product Integration

The System Engineering/Product Integration activity efforts include analyses of novel hot and warm gas cleaning technologies, CO_2 concentration using regenerable sorbents, membrane-based air and hydrogen separation technologies, and co-feeding applications. A strategy also will be developed and implemented for the development and validation of advanced models of gasification-based technologies and processes in support of Vision 21.

OVERVIEW

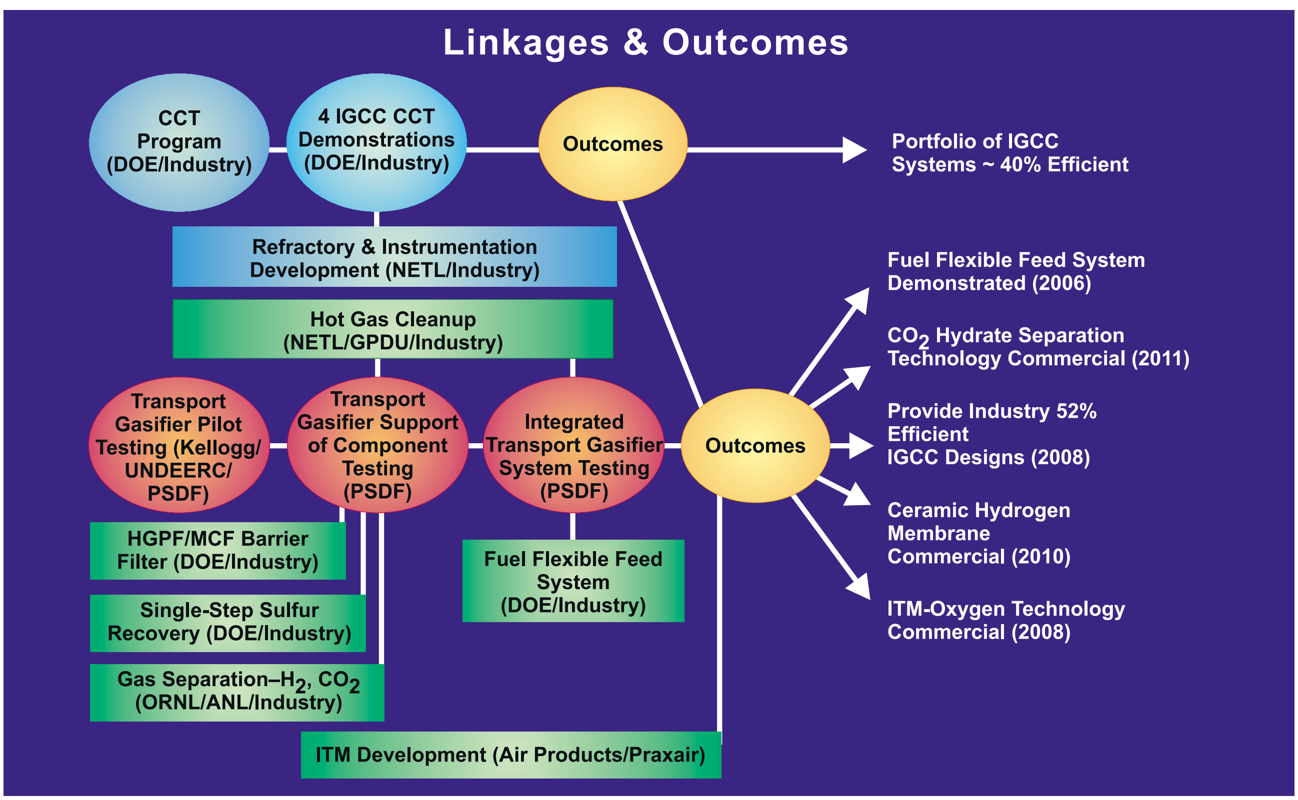
Links and Crosscuts

The exhibit below summarizes the linkages and outcomes in Gasification Technologies. Gasification Systems Technology efforts support both the introduction of advanced gasifiers with enhanced cost and performance, and the improvement of gasification technologies emerging from the CCT Program. The work on the transport gasifier takes place primarily at the PSDF and is supported by NETL, UNDEERC, and the technology developer, Kellogg Brown & Root (Kellogg). Also ongoing is development of advanced corrosion-resistant refractories to enhance performance of existing slagging coal gasifiers, and enable use of corrosive alternative feedstocks and development of instrumentation for real-time measurement of critical process conditions. Products from the refractory and instrumentation development are to be evaluated at CCT projects demonstrating IGCC. Development of a fuel-flexible feed system is ongoing in conjunction with industry to accommodate biomass, and industrial/municipal/agricultural/refinery wastes.

Gas cleaning and conditioning activities include HGPF and MCF development under the PFBC area and development of hot gas cleanup systems using regenerable sorbents. NETL supports hot gas cleanup through in-house research and testing of promising concepts, emerging from both in-house and DOE/industry joint research at their Gas Process Development Unit (GPDU). The PSDF is used for integrated subsystems testing.

Air Products and Chemicals, Inc. and Praxair are participating with NETL in the development of ionic transport membrane (ITM) and oxygen transport membranes for oxygen separation. Oak Ridge National Laboratory (ORNL) and Argonne National Laboratory (ANL) are developing hydrogen separation membranes. CO_2 and pollutant separation is a combined National Laboratory, university, and industry effort.

By-Products activities support ongoing CCT projects by improving the quality and marketability of ash and slag, and address single step sulfur removal processes at the PSDF. Synthesis gas utilization activities focus on ensuring coal-derived synthesis gas quality meets the needs of coproduction, in cooperation with the Fuels program, and meets the needs of fuel cell applications, in cooperation with the Distributed Generation program.



TURBINE ACTIVITIES

An ongoing Advanced Turbine Systems (ATS) program is scheduled to complete demonstration of two utility-scale turbines by 2002. These systems will be capable of achieving 60 percent efficiency on a lower heating value basis (LHV) and NO_x emissions less than 9 ppm. Research at NETL and an industry/university consortium continues to provide the technology base in materials science, combustion modeling and testing, heat transfer, instrumentation and controls, and aerodynamics. The ATS developments will be used to enhance the efficiency of the PFBC, gasification, and IFC systems.

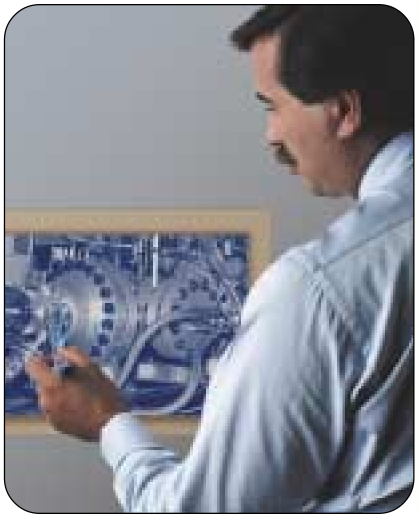
NETL Low-Btu Combustion Facility

A Next Generation Turbine (NGT) program has been initiated, drawing on the technology advances and lessons learned in structuring effective partnerships under the ATS program. The NGT program will again use industry/academia/government partnerships to achieve a new set of aggressive goals made feasible by the derivative technology from the ATS program. There are three elements of the NGT program — Systems Development and Integration; Reliability, Availability, and Maintainability (RAM) Improvement; and Crosscutting Research and Development.

Systems Development and Integration. Turbine systems will be developed to meet the needs of new, emerging, deregulated power supply markets. These systems will respond to stakeholder needs by providing highly efficient, reliable, and ultra-clean operations, and by offering flexibility to perform effectively independent of duty cycle or fuel used. Systems currently under evaluation and development are flexible turbine systems and turbine/fuel cell hybrids greater than 30 MW in output rating.

RAM Improvement. RAM Improvement efforts will develop the instrumentation, inspection and examination technology, analytical modeling, and evaluation techniques necessary to monitor turbine performance and determine when maintenance is needed based on turbine condition. System information technology platforms will be developed and demonstrated at host sites.

Crosscutting Research and Development. Crosscutting Research and Development will be conducted by a consortia of U.S. government organizations, industries, universities, and national laboratories. These consortia will provide combustion modeling, materials science, computer simulations, and instrumentation needed to support achievement of the program goals.



Links and Crosscuts

The exhibit on the next page summarizes the linkages and outcomes in Turbine Systems research and development. The ATS program was carried out by two major turbine manufacturers — General Electric (GE) and Siemens Westinghouse (SW) — with supporting research provided by NETL and an industry/ university consortium. The South Carolina Institute for Energy Studies (SCIES) directed the consortium, contracting universities to perform applied research specific to the needs of the ATS developers. As many as 100 U.S. universities have contributed to ATS develpoment.

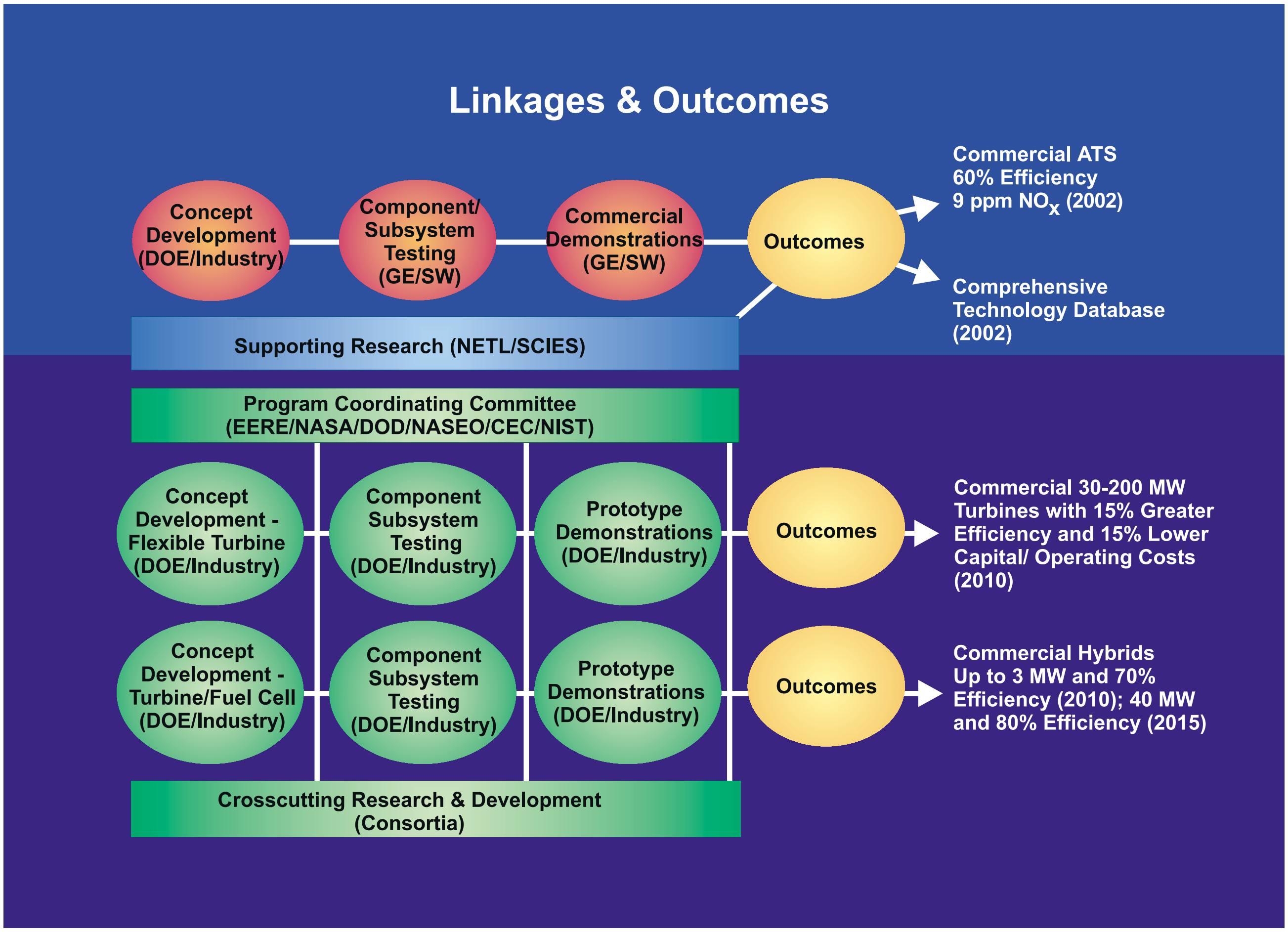
The NGT program intends to broaden public and private sector participation through workshops. More research contracts with industry are anticipated and a government sponsored committee is to be established to coordinate activities with the DOE Office of Energy Efficiency and Renewable Energy (EERE), National Aeronautics and Space Administration (NASA), Department of Defense (DoD), National Association of State Energy Officials (NASEO), California Energy Commission (CEC), National Institute for Standards and Testing (NIST), and other federal and state organizations. Specific linkages include: the EERE micro-turbine program, NASA Ultra-Efficient Engine Technology program (UEET), and DoD propulsion programs — Integrated High Performance Turbine Engine Technology (IHPTET), Versatile, Affordable Advanced Turbine Engines (VAATE) program, and the Navy Future Ships programs. An Industry Peer Review Board is also being established to ensure program quality and relevance.

Four companies have been selected by DOE to define Flexible Turbine Systems: Rolls Royce Allison (RRA), Pratt and Whitney (PW), GE, and SW.

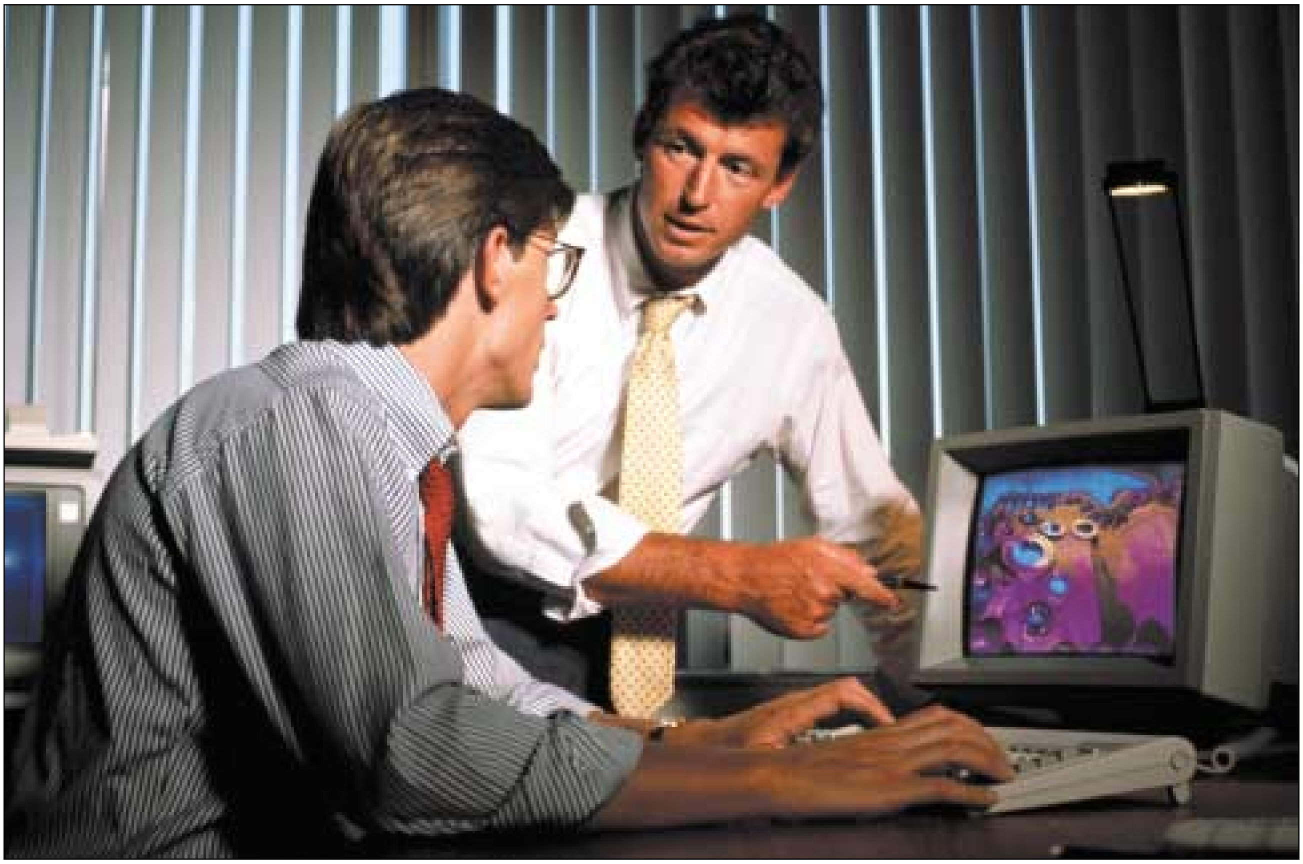
In Turbine/Fuel Cell Hybrids, systems studies by SW, RRA, FuelCell Energy (FCE), Caterpillar, and Northern Research and Engineering Corporation laid the foundation for follow-on efforts. DOE selected FuelCell Energy-Capstone Turbine and RRA to conduct 280-kW hybrid demonstrations and develop designs for a 40-MW hybrid system. DOE also has agreements with SW to conduct hybrid demonstrations at 250-kW and 1-MW scales. Both EPA and the European Commission anticipate partnering with DOE on the demonstrations.

Two companies are currently pursuing testing of NGT components — Ramgen Power Systems, Inc., and Clean Energy Systems. Both RAM Improvement and Crosscutting Research and Development activities will be implemented by consortia consisting of government organizations, industry, universities, and National Laboratories.

Photos by Siemens Westinghouse illustrate the complexity of turbine blades



Linkages & Outcomes
Concept Development (DOE/Industry)
Component/ Subsystem Testing (GE/SW)
Commercial Demonstrations (GE/SW)
Outcomes
Commercial ATS
60% Efficiency
9 ppm NO_x (2002)
Comprehensive Technology Database (2002)
Supporting Research (NETL/SCIES)
Program Coordinating Committee (EERE/NASA/DOD/NASEO/CEC/NIST)
Concept Development - Flexible Turbine (DOE/Industry)
Component Subsystem Testing (DOE/Industry)
Prototype Demonstrations (DOE/Industry)
Outcomes
Commercial 30-200 MW Turbines with 15% Greater Efficiency and 15% Lower Capital/ Operating Costs (2010)
Concept Development - Turbine/Fuel Cell (DOE/Industry)
Component Subsystem Testing (DOE/Industry)
Prototype Demonstrations (DOE/Industry)
Outcomes
Commercial Hybrids Up to 3 MW and 70% Efficiency (2010); 40 MW and 80% Efficiency (2015)
Crosscutting Research & Development (Consortia)



Drivers

- Existing coal-fired electric generating capacity must be retained to sustain economic growth.
- Retaining existing plants requires a portfolio of advanced environmental controls and repowering technologies to meet increasingly stringent emissions standards.
- To maintain or improve ambient air standards in most regions of the United States, new capacity additions will have to achieve near-zero pollutant emissions.
- Public policy is placing a premium on efficiency, use of renewable fuels, and elimination of solid waste.
- Natural gas-based power systems are expected to provide more than 90 percent of the 300 gigawatts of projected new domestic capacity by 2020.
- Utility restructuring requires power generators to shoulder the cost and risk of installing new capacity additions.
- Unprecedented worldwide growth in energy consumption is projected — a 60 percent increase by 2020 — with coal-dependent Asia and gas-dependent Central and South America accounting for nearly half of the growth.
- Fuel and product flexibility enhances the market potential of power systems by enabling use of low-cost indigenous and opportunity fuels, and production of vital chemicals and transportation fuels.
- Achieving radical improvements in performance of fossil fuel-based power systems and eliminating environmental barriers to fossil fuel use requires integration of power and fuel system "modules" into systems capable of meeting continuing cost and performance challenges.
- Stabilizing global greenhouse gas emissions requires both developed and developing countries to adopt advanced, high-efficiency power technologies.
- Concentrating carbon dioxide emissions from power systems facilitates capture and mitigates sequestration costs.

Objectives

- Disseminate results from the CCT program. (Present-2007)
- Complete development of retrofit NO_X control technologies necessary to meet the latest ambient air standards for ozone and $PM_{2.5}$ levels. (2003)
- Demonstrate technologies to effectively control up to 70 percent mercury emissions from coal-fired plants by 2005 and up to 90 percent by 2007.
- Complete development of data and technology to control primary and secondary $PM_{2.5}$. (2005)
- Develop CCB utilization options for existing plants by 2004 and advanced plants by 2006.
- Demonstrate a 60 percent efficient (LHV) natural gas-based Advanced Turbine System with NO_X emissions less than 9 ppm. (2002)
- Complete development of 30- to 200-MW NGT turbine with 15 percent improvement in efficiency and cost, and turbine/fuel cell hybrids with 70 percent efficiency. (2010)
- Complete proof-of-concept testing of LEBS. (2003)
- Demonstrate 52 percent efficient second-generation PFBC. (2008)
- Develop advanced gasifier and associated components and subsystems necessary to achieve fuel flexibility and greater than 52 percent efficiency in an IGCC mode. (2008)
- Develop gas purification and particulate cleanup components essential to second generation PFBC and gasification technology goals and for linking early hybrid systems to fuel cells. (2006)
- Complete commercialization of ITM-oxygen separation technology. (2008)
- Complete commercialization of ceramic hydrogen (H_2) separation membrane. (2010)
- Complete commercialization of CO_2 hydrate separation technology. (2011)
- Complete design of commercial-scale Vision 21 plants and simulate plants using virtual demonstration capability. (2015)

Strategies

- Build on the cost-shared government/industry CCT projects.
- Continue cooperative work with EPA, states, and industry to address current ambient NO_X, $PM_{2.5}$, and vapor phase mercury source emission issues.
- Continue cooperative work through the CBRC to characterize and develop uses for CCBs from existing and advanced power plants.
- Integrate ATS developments into new commercial turbine offerings, and use to enhance efficiency of PFBC and gasification technologies.
- Apply ATS lessons learned and supporting research to develop NGT products.
- Introduce LEBS as a substitute for conventional pulverized coal-fired systems in Asian market.
- Demonstrate second generation PFBC under the CCT program.
- Evaluate advanced refractory materials and instrumentation at existing CCT project sites demonstrating IGCC.
- Apply PSDF and in-house GPDU facilities to support cooperative research in fuel and product flexibility and process gas separation and cleanup.
- Use PSDF to develop advanced gasifier and associated components and subsystems necessary to achieve fuel flexibility and greater than 52 percent efficiency in an IGCC mode.
- Develop and use advanced computational technology and existing operating systems to demonstrate feasibility of Vision 21 systems.

Performance Measures

- Advanced environmental control and power system technologies reduce regulatory compliance costs by 25–75 percent and enable coal-fired units to maintain 50 percent of U.S. electric generating capacity.
- Leveraging fuel and product flexibility, gasification-based power generation is increased by 10,758 MWth in the near term. (2003)
- ATSs supplant current turbines, reduce pressure on natural gas supply in meeting growing electricity demand, and enhance performance of PFBC and IGCC. (2002)
- Flexible Gas Turbine Systems emerge and expand market applications. (2010)
- LEBS technology gives U.S. competitive position in overseas markets and results in exports. (2003)
- Success of first generation PFBC and IGCC overseas and in U.S. niche markets, and performance enhancements coming out of demonstration of second generation PFBC and fuel-flexible gasification technologies reduce costs to <$1,000/kW in the mid-term. (2008)
- IFC technology emerges as high-efficiency combustion module for Vision 21 systems. (2008)
- Gas separation membrane and high-temperature cleanup technology enable hybrid systems to achieve greater than 60 percent efficiency while reducing costs by 10-20 percent. (2010)
- Industry participants begin to site Vision 21 plants. (2015)

Central Power Program Benefits

National Benefits

- Sustains economic growth by maintaining low-cost electricity vital to the U.S. economy;
- Ensures energy security by using abundant indigenous resources for a significant component of the energy mix, and by using natural gas resources efficiently;
- Provides alternative means of producing critical chemicals and fuels;
- Responds to regional and global environmental concerns; and
- Establishes a strong U.S. environmental and power generation technology position for export to the world market.

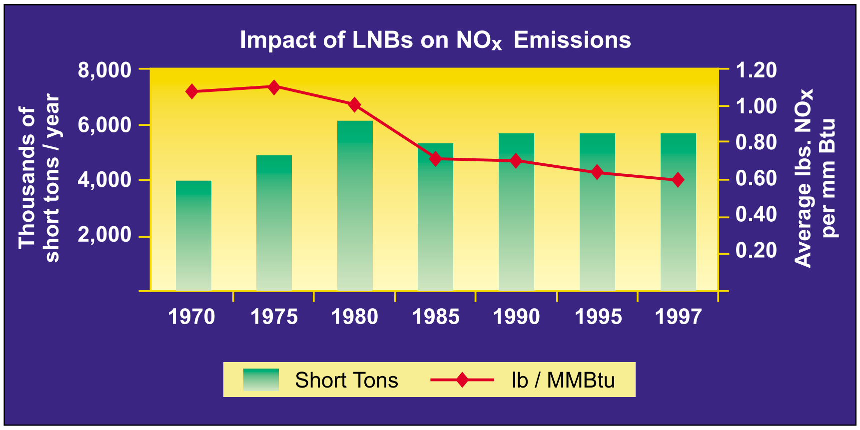
Supplier Benefits

- Enables electricity suppliers to cost-effectively adjust to regional energy and environmental demands;
- Broadens the market beyond simply supplying electricity; and
- Allows significant capacity additions at existing sites, which precludes the need for additional plant siting and transmission line installations.

Customer Benefits

- Maintains low-cost electricity rates, which are already among the lowest in the world;
- Provides U.S. industrial users a competitive edge for their products in the world marketplace;
- Serves to bolster electric generating capacity reserve margins critical to reliable service;
- Enhances the local, regional, and global environment; and
- Protects against price shocks in industrial chemicals and transportation fuels.

ADVANCED NO_x CONTROL



Performance Targets

NO_x Emissions: 0.15 lb/10^6 Btu

Levelized Cost: 25% less than SCR

Year: 2003

Advanced NO_x Control research is driven by continuing pressure for further reductions in NO_x emissions from coal-fired boilers to address ground-level ozone, ambient fine particulates, visibility, eutrophication, and climate change. The current portfolio of NO_x control activities ranges from modeling to full-scale demonstration. These efforts include the successful completion in April 2000 of a demonstration of SNCR technology at American Electric Power's 600-MWe Cardinal Plant in Brilliant, Ohio.

The success of the Advanced NO_x Control research is intimately tied to close coordination and cooperation with users, technology developers, and state agencies, and builds on success achieved through the CCT program. One such CCT program success was the development of low-NO_x burners (LNBs) applicable to over 90 percent of existing coal-fired capacity. Nearly half of the domestic coal-fired boiler population have incorporated LNBs. As shown in the adjacent table, LNBs nearly halve industry-wide emissions and stabilize annual emissions despite significant increases in coal-fired capacity.

Metering pumps for the Cardinal Plant SNCR system's urea injection

American Electric Power's 600-MWe Cardinal Plant in Brilliant, Ohio

Advanced NO_x Control activities include two major thrusts: (1) retrofitable NO_x controls capable of meeting Title I CAAA provisions for ozone and $PM_{2.5}$ (Title I NO_x Control); and (2) advanced low-NO_x combustion (ALNC) technology capable of far exceeding Title I CAAA provisions in response to projected future tightening of source emission and ambient air requirements.

Title I NO_x Control performance targets are to: (1) achieve NO_x emission rates of 0.15 lb/10^6 Btu or less; (2) reduce levelized costs by 25 percent relative to SCR; (3) produce negligible impact on balance of plant; (4) apply to most boiler types; and (5) maintain performance over a wide range of coals and operating conditions. The research portfolio sought includes advanced combustion controls, advanced flue gas treatment, and integrated control systems.

Title I NO_x Control activities are being carried out through collaborative research resulting from competitive solicitations under the Advanced Environmental Control Technologies (AECT) program, which addresses both primary and secondary $PM_{2.5}$ control. Recently concluded Phase I AECT investigations examined advanced reburning, SNCR, and SCR/SNCR hybrid technologies. Under Phase II, the NO_x control focus is on development of: (1) a second-generation advanced reburning (SGAR) process using reagent injection, sponsored by Energy and Environmental Research Corporation (EERC); and (2) an SNCR/SCR hybrid process sponsored by GPU Generation, Inc.

The SGAR system achieved 98 percent NO_x removal at 1 x 10^6 Btu/hour pilot scale and will be scaled-up to 10 x 10^6 Btu/hour under Phase II testing. GPU Generation is carrying out a full-scale demonstration of the SNCR/SCR hybrid at the 147-MWe Seward Station near Johnstown, Pennsylvania, with co-funding from EPRI, CONSOL, and EPA.

The work is expected to result in control options for power generators in the 2002–2004 time frame to support NO_x SIP Call compliance and satisfy the $PM_{2.5}$ control milestone for NO_x precursor control.

ALNC concepts are being sought through competitive solicitation that include oxygen enhanced combustion. ALNC goals are more long-term, with pilot-scale testing projected by 2005 and commercial design availability by 2007. These activities support Vision 21 Advanced Emission Control goals of near-zero emissions by 2015.

SCR test facility at Gulf Power Company's Plant Crist

$PM_{2.5}$/Air Toxics Control

Performance Targets

Establish Source-Receptor Relationships

$PM_{2.5}$ Capture:
99.99% by 2007

Mercury Capture:
50% by 2005
90% by 2010

There are three basic thrusts to the $PM_{2.5}$/Air Toxics Control activity: (1) $PM_{2.5}$ characterization analyses, (2) $PM_{2.5}$ control development, and (3) mercury control development.

$PM_{2.5}$ characterization analyses combine ambient air monitoring and source emission characterization. Ambient air monitoring evaluates the concentration and chemical and physical composition of $PM_{2.5}$, $PM_{2.5}$ precursor gases, ozone, and mercury in order to provide improved resolution of deposition patterns and source-receptor relationships. Source emissions entails evaluation characterization of both primary and secondary $PM_{2.5}$ from fossil fuel-based power systems to better understand their potential impacts on ambient air quality and regional haze and their role in human exposure. Included in the source emissions characterization are investigations into the atmospheric formation and transport mechanisms associated with $PM_{2.5}$, and the interactions between secondary $PM_{2.5}$ and ozone precursors.

NAAQS calls for the establishment of a national network of 1,500 $PM_{2.5}$ monitors, starting in 1998, to identify areas of attainment and non-attainment with the new $PM_{2.5}$ standard. Some 300 sites will be used to collect data on chemical characteristics and a small subset of these will include "supersites" to provide increased temporal, chemical, phase, and size fraction resolution of $PM_{2.5}$ measurements. DOE's role is to establish and operate several $PM_{2.5}$ supersites.

DOE's monitoring effort is composed of four sites (two major and two supplemental) under the Upper Ohio River Valley Project (UORVP), and five (one major and four supplemental) under the Steubenville Comprehensive Air Monitoring Project (SCAMP). The ambient air research station at NETL in South Park, Pennsylvania, forms the third key component of the regional monitoring network. A fourth project, the Carnegie-Mellon University (CMU)/EPA Pittsburgh Supersite, was selected by DOE under a Fiscal Year 2000 broad-based solicitation.

The primary sites in the UORVP are the Lawrenceville, Pennsylvania urban site operated by the Allegheny County Health Department, and the Holbrook, Pennsylvania rural monitoring facility located at a site operated by the Pennsylvania Department of Environmental Protection. Lawrenceville and Holbrook contain several types of filter-based particulate matter monitoring equipment, continuous samplers for co-polluting gases, and surface meteorological stations. The UORVP is scheduled to complete sampling in the summer of 2001 and enter the principal analysis and interpretation phase later this year.

The SCAMP site is a location featured in the 1993 Harvard University School of Public Health "Six Cities" study cited by EPA in establishing ambient $PM_{2.5}$ standards because of correlations noted in the study between ambient $PM_{2.5}$ mass and adverse health effects. The SCAMP project, which includes both indoor and outdoor monitoring, will offer complete characterization of the relationships between ambient $PM_{2.5}$ and human exposure, including the chemical components of $PM_{2.5}$ at various locations. The information will provide a comprehensive database for use in subsequent epidemiological studies, long-range transport studies, and State Implementation Program development. CONSOL Energy is the primary performer of SCAMP, and will provide the necessary coordination and data integration between the various components of the study.

DOE is supporting the outdoor SCAMP study, which includes daily, and in some cases, continuous measurements of $PM_{2.5}$ mass and composition. For the outdoor study, which began measurements in the summer of 2000, CONSOL has formed a team with the Harvard University School of Public Health, Ohio University, Franciscan University of Steubenville, Wheeling Jesuit University, and Saint Vincent College. The indoor component of SCAMP is being performed by the

Harvard University School of Public Health under subcontract to CONSOL, and is supported by a consortium of non-DOE sources.

The Pittsburgh supersite, located on the CMU campus, will expand on the DOE/NETL UORVP by adding a wide range of state-of-the-art measurements and increasing monitoring frequency. An ultimate goal is the development and evaluation of current and next-generation aerosol monitoring techniques. Both DOE and EPA will collaborate in the effort with a team from academia, private industry, and local and state air pollution agencies.

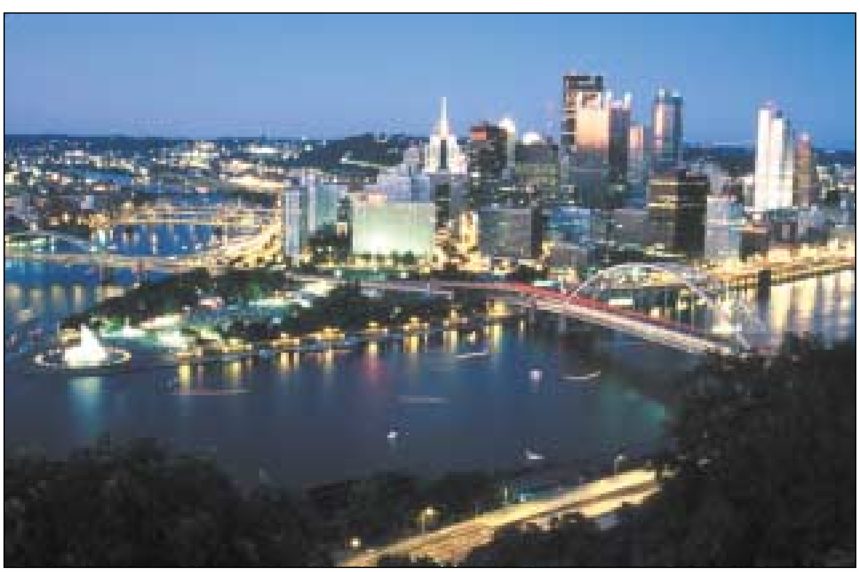
Baseline monitoring at the central Pittsburgh site is planned for an 18-month period that will include detailed characterization of particulate matter size, surface, volume distribution, and chemical composition — all as a function of size and on a single particle basis. Three 14-day intensive sampling periods are planned to examine temporal variation and to collect detailed data for model testing and validation.

The CMU project also will create a database of ambient particulate matter measurements for source-receptor and deterministic modeling in the Pittsburgh region. Estimates will be made of the impact of the various sources (transportation, power plants, natural, etc.) to the particulate matter concentrations in the area.

In a separate effort (not co-funded by DOE), EPA will conduct comprehensive modeling, and epidemiology and indoor exposure studies to test critical hypotheses relating to health effects, exposure, and control strategies.

Also, through an Interagency Agreement, DOE is partnering with the Tennessee Valley Authority (TVA), EPRI, and state and local environmental agencies to evaluate the impact of $PM_{2.5}$ on visibility in the Great Smokey Mountain (GSM) National Park in Tennessee. A supersite is being established in the GSM to address the degree to which emissions of sulfur and nitrogen oxides from power plants contribute to $PM_{2.5}$ and regional haze. As part of the TVA Interagency agreement, DOE also is supporting the Aerosol Research Inhalation Epidemiology Study in Atlanta, Georgia.

Source emission characterization is aimed at developing better source "signatures" that can be used in source-receptor modeling and human exposure studies, and developing instrumentation and methods for sampling $PM_{2.5}$ in the absence of no direct sampling methods. Specific activities include: (1) plume and atmospheric chemistry studies at TVA's Cumberland station using fully instrumented helicopters; (2) NETL in-house combustion emission characterization; (3) McDermott Technology, Inc. LNB emission characterization focused on ultra-fine soot formation; and (4) Brookhaven National Laboratory development of perflourocarbon tracer technology for tagging source emissions.



The $PM_{2.5}$ characterization analyses follow parallel paths of ambient air monitoring and source emission characterization through 2002, converging into models defining source-receptor relationships in the 2003–2004 time frame. The parallel efforts will support EPA's five-year scientific review of the efficacy of fine particulate NAAQS due in 2002. The follow-on activities will contribute to $PM_{2.5}$ control development and SIP strategies for compliance.

$PM_{2.5}$ control development seeks to develop and evaluate technologies to cost-effectively control both primary and secondary $PM_{2.5}$. Activities to address NO_x precursor control are being pursued under Advanced NO_x Control, and are to be integrated into the $PM_{2.5}$ control development technology portfolio. The current focus of research under $PM_{2.5}$ control development is on controlling primary $PM_{2.5}$ emissions. Extensive emissions monitoring at coal-fired plants, through a DOE/EPA/industry coordinated effort, firmly established that trace elements and other air toxics are largely bound to the ash. Control of airborne toxics is, therefore, largely a function particulate matter collection efficiency. While particulate matter controls such as electrostatic precipitators (ESPs) and fabric filter baghouses have evolved into highly efficient systems (99 percent capture efficiency for total particulates), capture efficiency for particulates in the 0.01–10 micron range is far lower.

As in the case of precursor NO_x control development, primary $PM_{2.5}$ control activities are being carried out through collaborative research resulting from competitive solicitations under the AECT program. Phase I AECT investigations have concluded and Phase II development is underway. Performance targets are 99.99 percent capture of all particle sizes in the range of 0.01–10 microns, an emissions rate not to exceed 0.01 lb/10^6 Btu, and levelized cost savings of 25 percent relative to conventional systems.

Phase II projects include: (1) the UNDEERC development of an advanced hybrid particulate collector (AHPC) that combines the best features of ESPs and baghouses in a novel configuration; and (2) ABB Combustion Engineering development of an ESP using cooling, humidification, sorbent injection, and pulsed energizing. Both concepts will move to pilot-scale testing under Phase II.

Assessments of the Phase II concepts are scheduled through 2003. Precursor NO_x control options are to be made available in the 2003–2004 time frame, which is addressed in the Title I NO_x control effort. All $PM_{2.5}$ control options are to be completed by 2007.

Mercury control development draws upon prior efforts in augmentation of existing flue gas cleanup controls and stand alone control concepts, and seeks the most promising mature concepts for field testing and novel concepts for pilot testing.

Prior work included sorbent injection techniques for direct mercury capture, and catalytic conversion of mercury to a soluble form for capture in wet scrubbers. In 2000, DOE issued a solicitation for industry proposals on cost-cutting mercury control methods for coal-based power systems. Also considered will be controls that remove mercury along with other pollutants, including sulfur trioxide, carbon dioxide, nitrous oxides, and hydrogen chloride. Assessments are to take place for three years.

The goal is to develop more effective options that will cut mercury emissions 50–70 percent by 2005, and 90 percent by 2010 at one-quarter to one-half of current cost estimates.

All $PM_{2.5}$/Air Toxics Control activities support the goal of negligible primary and secondary $PM_{2.5}$ constituents from Vision 21 plants.

$PM_{2.5}$ and sequential filter samplers at Holbrook monitoring site, UORVP

Central SCAMP monitoring site, Steubenville, Ohio

PROGRAM AREAS

Coal Combustion By-Products

Performance Targets

Increase CCB Utilization Rate from 30% to 50% by 2010

Coal combustion by-products (CCBs) include flyash, bottom ash, boiler slag, and flue gas desulfurization (FGD) residues. The CCB activities follow industrial ecology principles of recycling, or utilizing in some other manner, all process effluents that would otherwise be regarded as waste streams. The activities include: (1) addressing identified barriers to widespread CCB use through application of science and technology and technology transfer; and (2) addressing evolving CCB issues associated with application of advanced power generation and pollution control systems. The goal is to increase the CCB utilization rate from the current 30 percent to 50 percent by 2010.

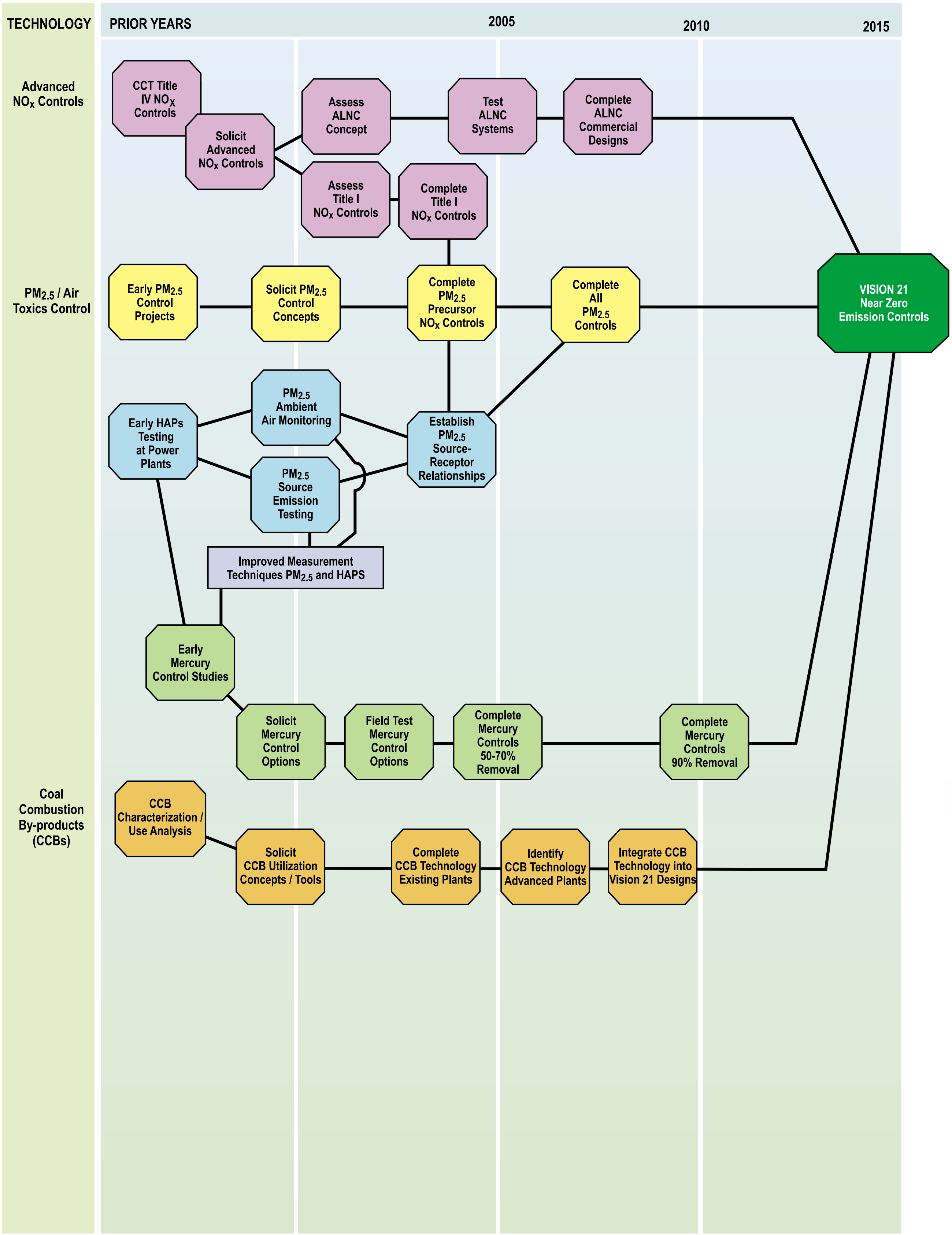
Drawing upon previous CCB characterization and utilization work, the Combustion By-Products Recycling Consortium issued a regionally based solicitation in May 2000 for: (1) research into utilization issues introduced by NO_x controls; (2) unique utilization techniques and technologies; (3) development of standards for state and federal use specifications; (4) development of tools to assess benefits of CCB use; and (5) development of information processes to promote CCB use. Solicitation targets are to achieve, by 2005, a doubling of the current rate of FGD by-product use, a 10 percent increase in overall national rate of by-product use, and a 25 percent increase in the number of uses considered "allowable" under state and federal regulations.

Plans are to continue activities on all fronts, with the goal of having a portfolio of technologies and information systems in place to significantly enhance use of CCBs from existing plants by 2004. Similar CCB management tools are expected for advanced power systems by 2006. Integration of CCB technologies into Vision 21 plant designs is scheduled for 2008.

The following roadmap summarizes activities under the three Innovations for Existing Plants program areas.

Current FGD residue disposal method

ROADMAP


TECHNOLOGY
PRIOR YEARS
2005
2010
2015
Advanced NOx Controls
PM2.5 / Air Toxics Control
Coal Combustion By-products (CCBs)
CCT Title IV NOx Controls
Solicit Advanced NOx Controls
Assess ALNC Concept
Test ALNC Systems
Complete ALNC Commercial Designs
Assess Title I NOx Controls
Complete Title I NOx Controls
Early PM2.5 Control Projects
Solicit PM2.5 Control Concepts
Complete PM2.5 Precursor NOx Controls
Complete All PM2.5 Controls
VISION 21 Near Zero Emission Controls
Early HAPs Testing at Power Plants
PM2.5 Ambient Air Monitoring
PM2.5 Source Emission Testing
Establish PM2.5 Source-Receptor Relationships
Improved Measurement Techniques PM2.5 and HAPS
Early Mercury Control Studies
Solicit Mercury Control Options
Field Test Mercury Control Options
Complete Mercury Controls 50-70% Removal
Complete Mercury Controls 90% Removal
CCB Characterization / Use Analysis
Solicit CCB Utilization Concepts / Tools
Complete CCB Technology Existing Plants
Identify CCB Technology Advanced Plants
Integrate CCB Technology into Vision 21 Designs

Low-Emissions Boiler System

Performance Targets

Efficiency: 42% HHV

Emissions:
NO_x – 0.1 lb/10^6 Btu
SO_2 – 0.1 lb/10^6 Btu
PM – 0.01 lb/10^6 Btu

Year: 2003

The Low-Emissions Boiler System (LEBS) is an advanced pulverized coal-fired system that integrates environmental controls into the design and uses a supercritical steam cycle to significantly enhance performance.

Three teams were competitively selected to participate on a cost-shared basis in the LEBS program. Three boiler manufacturers headed up technology teams, each with a "user" advisory panel composed of utilities and non-utility generators. After engineering development and testing, the three industry teams submitted designs for a 400-MWe commercial plant along with proof-of-concept (POC) approaches. In September 1997, the D.B. Riley team was selected to construct and operate an 80-MWe LEBS unit in Elkhart, Illinois.

The D.B. Riley LEBS design features a novel U-fired furnace and moving-bed copper-oxide flue-gas cleanup system. The U-fired furnace converts nearly all of the coal ash into a glass-like slag, which represents about one-third of the volume of fly ash and is a high-value product used as blasting grit and roofing granuals. Particulate matter (PM) is controlled by a fabric filter. To further reduce or eliminate solid waste management problems, the copper-oxide moving-bed system employs a reusable alumina-based, copper-oxide coated sorbent for SO_2 and NO_x removal.

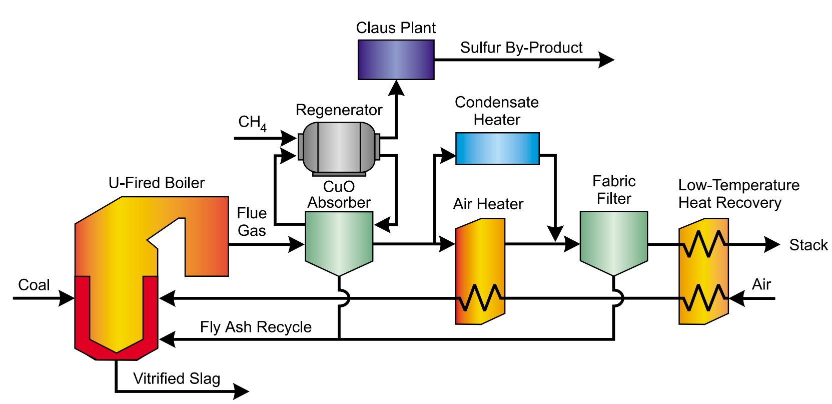
Up to 99 percent SO_2 removal is achieved by reacting with the copper-oxide on the alumina sorbent and oxygen to form copper sulfate. The sulfated sorbent is regenerated by introducing methane (CH_4), which removes the sulfur as a concentrated stream of SO_2 easily converted to high-value sulfur products.

NO_x control starts in the U-fired furnace where combustion is staged by reburning — a process creating a fuel-rich zone above the main burners to strip oxygen from nitrogen compounds, and completing combustion in an oxygen-rich zone at relatively low temperatures. Further NO_x reduction is achieved by injecting ammonia upstream of the sulfated sorbent, which serves as a catalyst to convert ammonia and NO_x into nitrogen and water.

LEBS will exceed New Source Performance Standards for pollutant emissions and has an efficiency of 42 percent or greater.

Plans are to conduct POC testing on the U-fired furnace at 80-MWe scale. Commercial design of the U-fired furnace is expected to emerge directly from the POC testing. The copper-oxide process may require an additional scale-up to achieve commercialization. These technologies, and high-temperature materials developments supporting supercritical steam cycle advancement, will become base technologies for Vision 21 combustion systems.

Low-Emissions Boiler System



Advanced, low-NO_X, U-fired boiler produces environmentally benign inert slag

Copper-oxide flue-gas cleanup system removes 96%–99% of SO_2 and, if needed, 99% of NO_X

Heat recovery to air, condensate

Fabric filter for particulate collection

Air heater recovers heat from flue gases for increased efficiency

Indirect Fired Cycles

Performance Targets

Efficiency: 55% HHV

Emissions:

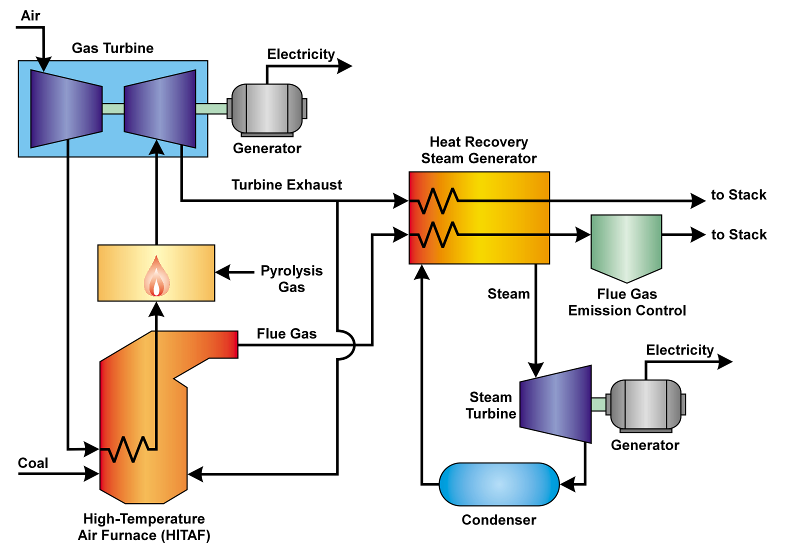
NO_x – 0.06 lb/10^6 Btu

SO_2 – 0.06 lb/10^6 Btu

PM – 0.003 lb/10^6 Btu

Year: 2010

Indirect Fired Cycle



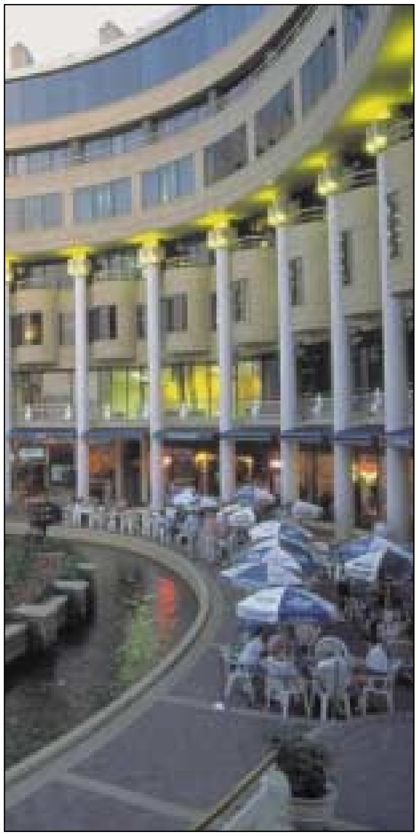
Indirect Fired Cycle (IFC) activities build on concepts and components emerging from two competitively selected teams developing High Performance Power Systems (HIPPS). HIPPS designs feature use of: (1) a high-temperature air furnace (HITAF) to transfer the heat of combustion to a clean working medium (air); and (2) coal pyrolysis and pyrolysis gas cleanup to produce a clean coal-based gas for combustion.

The adjacent schematic shows the conceptual application of HITAF and coal pyrolysis components. Air under pressure from a gas turbine compressor is heated in the HITAF and receives a further energy boost from combustion of clean pyrolysis gas before expanding in the gas turbine. Heat recovered from the gas turbine exhaust and HITAF flue gas is used to raise steam for a steam turbine (combined cycle).

The advantage of IFC lies in producing a clean, high-temperature working medium, which enables use of highly efficient, high-temperature gas turbines. While gas turbines offer increasingly greater efficiency with temperature, gas turbine components become increasingly susceptible to chemical corrosion and erosion as temperatures rise. Furthermore, the gas turbine Brayton cycle is inherently more efficient than the steam cycle, and use of the gas turbine/steam turbine combined cycle leverages efficiency. IFC avoids hot gas cleanup systems and the associated temperature limitations. IFC designs emerging from the HIPPS effort are targeting efficiencies of 55 percent.

IFC activities are focused on further development and systems studies of those components and subsystems identified in the HIPPS projects as having the greatest potential for supporting Vision 21 goals. United Technologies Research Center (UTRC) is pursuing HITAF development and Foster Wheeler Development Corporation is addressing pyrolyzer and pyrolysis gas cleanup. Plans are to tie the pyrolysis and pyrolysis gas cleanup work into PFBC support work at the PSDF.

For the period 2001–2006, HITAF, pyrolyzer, and fuel gas cleanup component/subsystem development will proceed in parallel with system studies to explore optimum advanced concepts. Advanced concepts in support of Vision 21 goals are to be selected for further development.



Pressurized Fluidized-Bed Combustion

Performance Targets

Efficiency: 52% HHV

Emissions:

- NO_x – 0.06 lb/10^6 Btu
- SO_2 – 0.06 lb/10^6 Btu
- PM – 0.003 lb/10^6 Btu

Cost: <$1,000/kW

Year: 2008

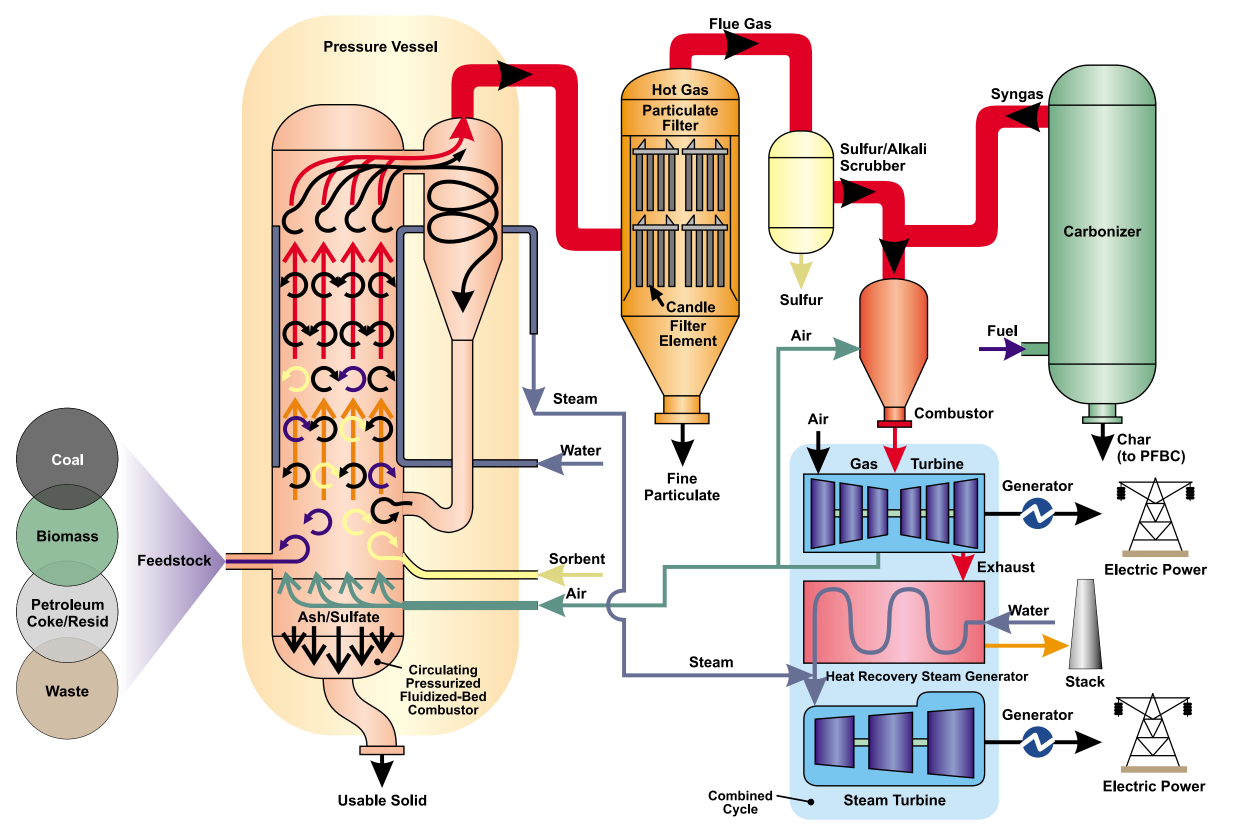
Fluidized-bed combustion (FBC) uses air to entrain and induce a turbulent mixing action to solid fuels and sorbent materials. The result is very low NO_x emissions through efficient combustion at temperatures of 1,400–1,700 °F, well below the thermal NO_x formation temperature (2,500 °F), and efficient SO_2 capture through effective sorbent/flue gas contact.

FBC performance is enhanced by performing the combustion under pressure (up to 30 atmospheres) in what is called pressurized fluidized-bed combustion (PFBC). Pressure improves combustion and sorbent capture efficiency, and generates sufficient flue gas energy to drive a gas turbine, which can be used in a combined cycle for further efficiency gains.

Under the CCT program, American Electric Power sponsored demonstration of ABB Carbon PFBC technology. ABB Carbon's PFBC is a first-generation system, which simply uses the energy derived in the PFBC boiler to drive a gas turbine in a combined-cycle mode. The resultant commercial ABB Carbon system, offering a nominal 40 percent efficiency, is currently realizing market penetration.

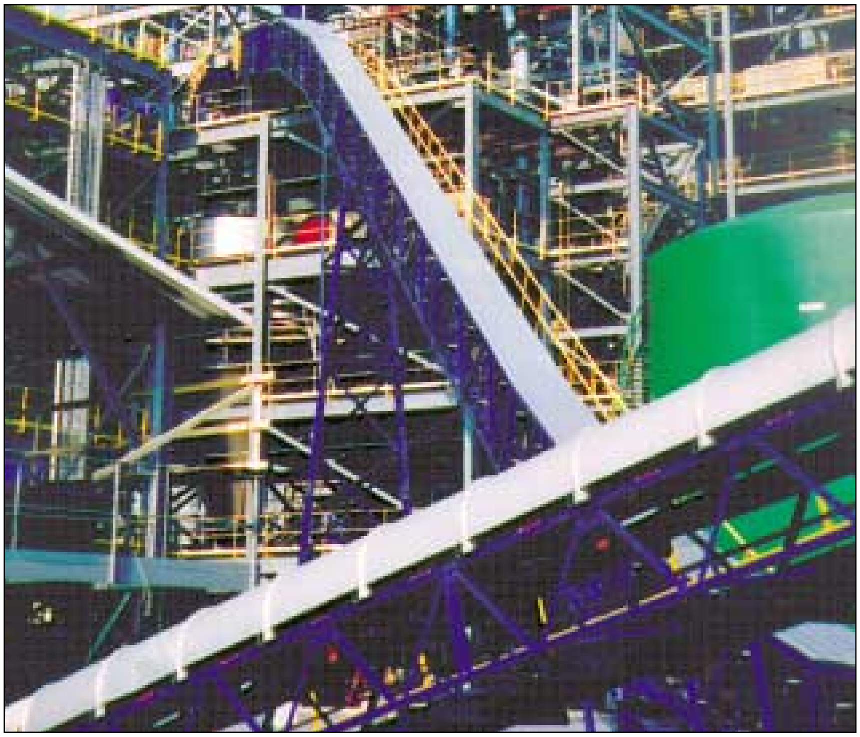
DOE efforts now are directed toward development of a second-generation PFBC having significantly higher efficiency and lower emissions and cost than first-generation systems. Emphasis is on enabling use, and fully utilizing the potential of advanced high-temperature, high-efficiency gas turbines. By realizing this potential, PFBC efficiencies greater than 50 percent are possible.

Second Generation PFBC



Activities in support of integrating and fully utilizing advanced gas turbines include: (1) integrating a coal pyrolysis (carbonizer) unit to produce fuel gas for combustion in the gas turbine; (2) a low-NO_x burner to combust the fuel gas; and (3) hot gas particulate filtration and chemical contaminant removal systems capable of operating at combustion and carbonizer exit gas temperatures (1,200–1,700 ^oF).

To further leverage PFBC and address future environmental concerns, parallel efforts are ongoing to: (1) develop more efficient sorbents to reduce operating costs and CO_2 emissions; (2) pursue cofiring of carbon neutral fuels; (3) ensure effective control of HAPs; and (4) conduct systems studies on integrating supercritical steam and fuel cell cycles.



The Power Systems Development Facility, located in Wilsonville, Alabama and operated by Southern Company Services, focuses on power system components and subsystems

Much of the PFBC development is to be carried out at the PSDF in Wilsonville, Alabama, operated by industry under a cost-shared partnership with DOE. The facility employs an innovative transport reactor to simulate fluidized-bed combustion flue gas streams and gasifier syngas, which enables evaluation of gas stream cleanup systems. Also in place is a PFBC unit consisting of a circulating pressurized fluidized-bed combustor, low-NO_x Multiannular Swirl Burner, and an HGPF system comprised of cylindrical ceramic filter element arrays (candle filters).

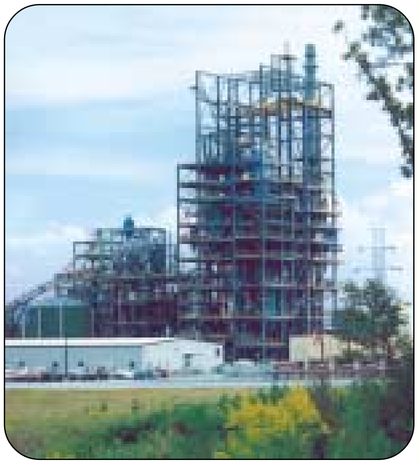
Plans are in place to complete development of ceramic and metallic candle filter-based HGPF systems (filter elements, failsafes, and support system) by 2002. Research on alternate HGPF materials and configurations will proceed in parallel, resulting in pilot-scale tests of advanced HGPF designs (ceramics for combustion and metallic for gasification) in 2004.

Multi-contaminant filter (MCF) concepts addressing gas phase chemical contaminates will be solicited in 2001, and will be integrated with advanced HGPF systems in 2005. In 2006, pilot-scale tests of an MCF/HGPF barrier filter system are to be conducted.

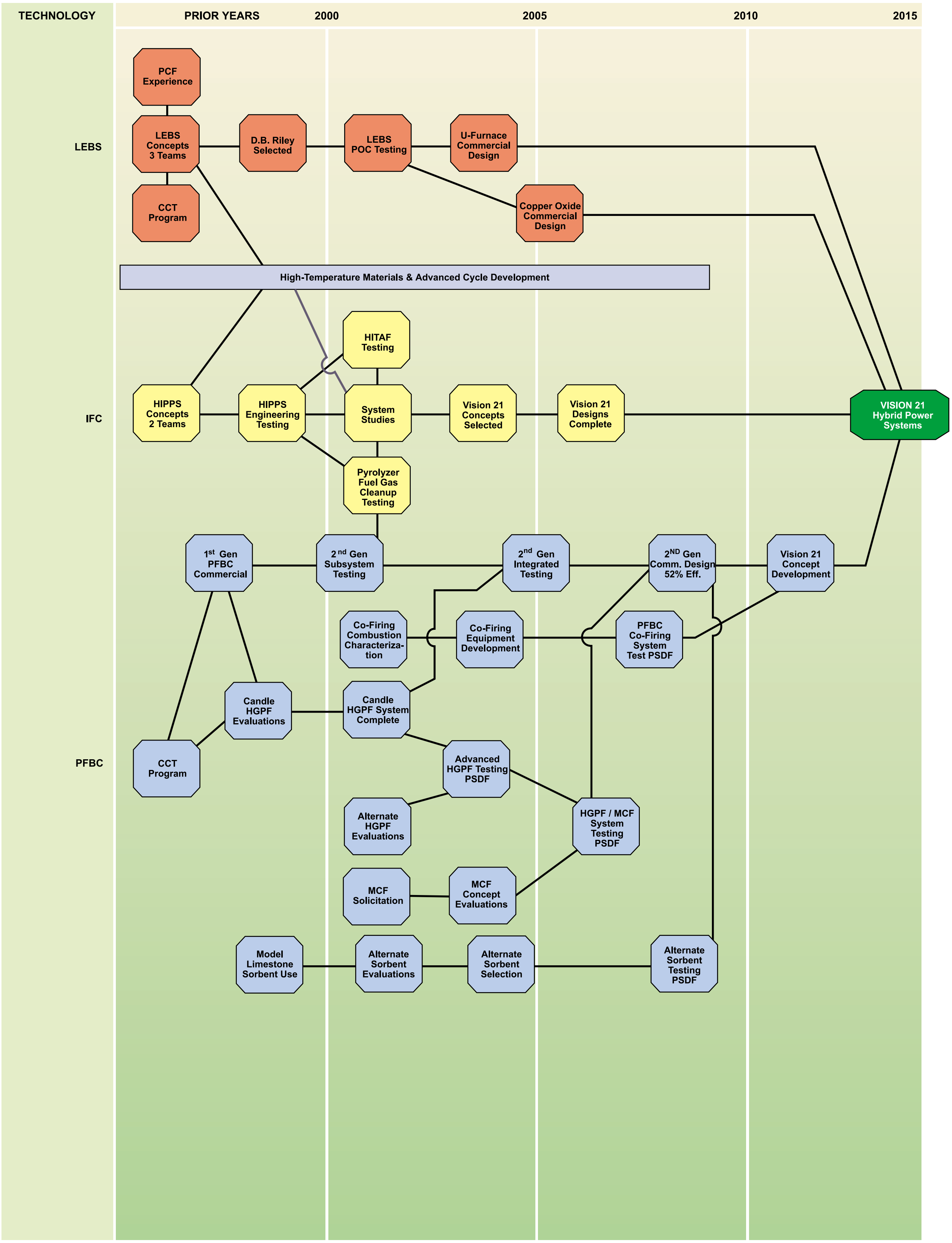
Development of a limestone sorbent utilization model to optimize sulfur capture and minimize solid by-product is to be completed by 2001. Evaluation of alternate fluidized-bed combustion sorbents will begin in 2001, concluding in pilot-scale testing of selected sorbents in 2008.

PFBC systems plans include integrated pilot-scale testing of a second-generation PFBC at the PSDF in 2005, and development of a 52-percent efficient second-Pgeneration PFBC by 2008. Combustion characterization of co-fired carbon neutral fuels, such as biomass, in 2001 and subsequent development of appropriate feed, sorbents, and cleanup systems will lead to a PFBC co-firing capability by 2007. PFBC concepts, integrating other Vision 21 enabling technologies such as fuel cells, are to be developed by 2010.

The roadmap on the following page summarizes activities under the three Combustion Systems program areas.



ROADMAP


TECHNOLOGY
PRIOR YEARS
2000
2005
2010
2015
LEBS
PCF Experience
LEBS Concepts 3 Teams
D.B. Riley Selected
LEBS POC Testing
U-Furnace Commercial Design
CCT Program
Copper Oxide Commercial Design
High-Temperature Materials & Advanced Cycle Development
HITAF Testing
IFC
HIPPS Concepts 2 Teams
HIPPS Engineering Testing
System Studies
Vision 21 Concepts Selected
Vision 21 Designs Complete
VISION 21 Hybrid Power Systems
Pyrolyzer Fuel Gas Cleanup Testing
1st Gen PFBC Commercial
2nd Gen Subsystem Testing
2nd Gen Integrated Testing
2ND Gen Comm. Design 52% Eff.
Vision 21 Concept Development
Co-Firing Combustion Characteriza-tion
Co-Firing Equipment Development
PFBC Co-Firing System Test PSDF
Candle HGPF Evaluations
Candle HGPF System Complete
PFBC
CCT Program
Advanced HGPF Testing PSDF
Alternate HGPF Evaluations
HGPF / MCF System Testing PSDF
MCF Solicitation
MCF Concept Evaluations
Model Limestone Sorbent Use
Alternate Sorbent Evaluations
Alternate Sorbent Selection
Alternate Sorbent Testing PSDF

Gasification Technologies

Performance Targets

Efficiency: >52%

Emissions:

NO_x – 0.06 lb/10^6 Btu
SO_2 – 0.06 lb/10^6 Btu
PM – 0.003 lb/10^6 Btu

Cost: <$1,000/kW

Year: 2008

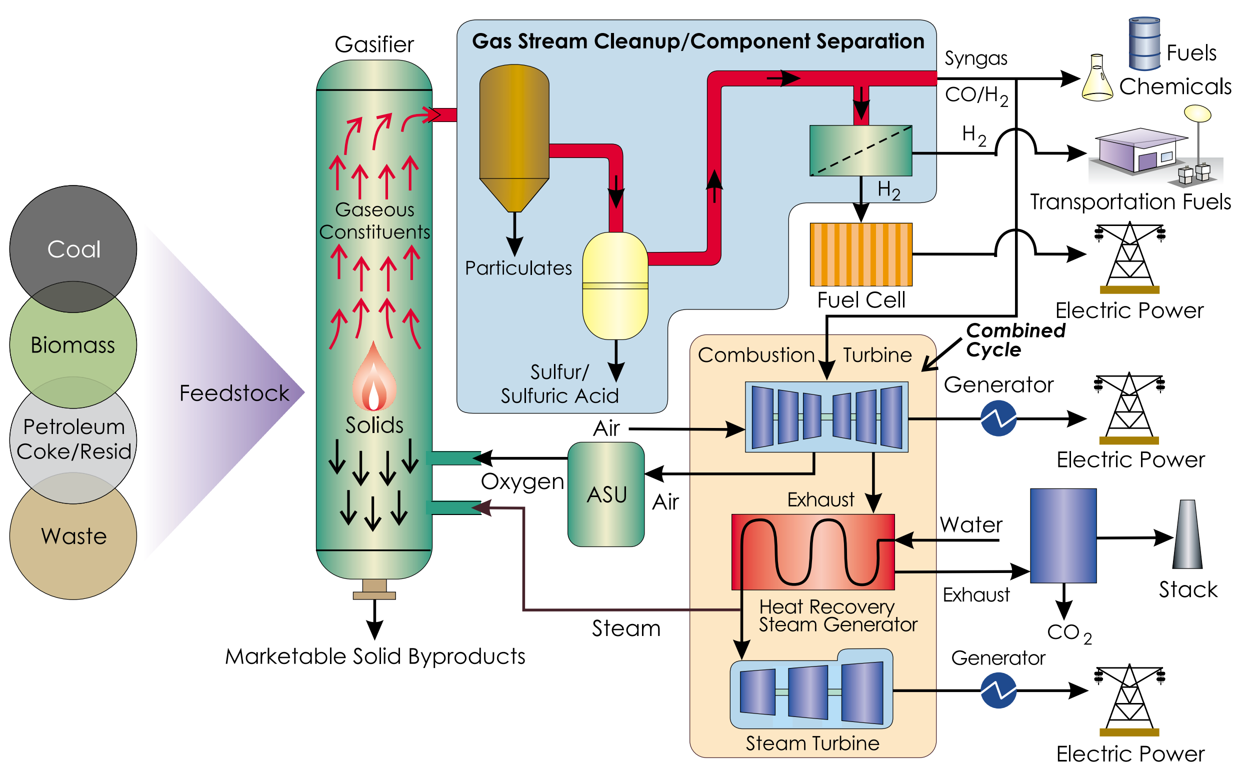
Gasification technologies represent the next generation of solid feedstock-based energy production systems. The heart of these systems is the gasifier. This unit is responsible for converting any carbon-based feedstock into synthesis gas (syngas), which is a mixture of carbon monoxide (CO) and hydrogen (H_2). This conversion is accomplished under high pressures and temperatures in the presence of steam and air/oxygen. Under these conditions, chemical bonds in the feedstock are broken and the constituents are further reacted to form synthesis gas.

The mineral matter in the feedstock separates from the gaseous products and leaves the bottom of the gasifier either as an inert glass-like slag or other marketable solid product. The synthesis gas from the gasifier, in addition to containing CO and H_2, also has smaller quantities of hydrogen sulfide, methane, ammonia, and particulate matter. The synthesis gas subsequently is cleaned of these impurities to meet downstream process unit requirements.

Once cleaned, the synthesis gas can be used, in whole or in part, to produce electricity, steam, fuels, chemicals, hydrogen, and substitute natural gas. One configuration of gasification-based processes, IGCC, uses clean synthesis gas to fuel a gas turbine. The gas turbine drives an electric generator and its exhaust gas is used to produce steam to drive a steam turbine/generator. IGCC is one of the most efficient and environmentally friendly of today's commercially advanced power generation technologies, and can be further enhanced through integration with fuel cells.

Gasification-based processes are the only advanced technologies that offer both feedstock and product flexibility, while simultaneously

Gasification-Based System Concepts



achieving near-zero emissions of sulfur, nitrogen oxides, and particulates. High operating efficiency of future gasification technologies (>52 percent) reduces CO_2 emissions, and the processes are readily adaptable for concentrating the remaining CO_2 for sequestration, a Vision 21 requirement. Through the development of advanced technologies, capital costs are expected to be reduced to below $1,000/kW by 2008, making gasification competitive with natural gas combined-cycle, and the technology of choice for solid feedstocks.

To meet energy market demands and facilitate global commercial acceptance of gasification-based technologies, the program strategy emphasizes increased efficiencies, cost reduction, high system reliability and availability, feedstock and product flexibility, and near-zero emission of pollutants. The strategy consists of two key elements: Gasification Systems Technology, and Systems Analysis/Product Integration.

Wabash River Generating Station was repowered with a 262-MWe IGCC unit shown here

Gasification Systems Technology

Gasification Systems Technology supports both the introduction of new gasifiers with enhanced cost and performance characteristics, and the improvement of gasification technologies emerging from the CCT program.

Advanced gasification activities in the area of new gasifier development are primarily directed at a novel entrained-flow transport gasifier, which offers the potential for high efficiency, fuel flexibility, and low capital cost. Exploration continues in parallel for other emerging novel concepts that show promise. Development work on the transport gasifier is currently centered at the PSDF and supported by the developer, Kellogg Brown & Root, NETL, and UNDEERC. The 2-ton/hour pilot-scale transport gasifier at the PSDF will serve as both a development unit and support unit for key gasification technology and PFBC component development.

Supporting research for enhancing gasification technology performance includes development of: (1) fluid dynamic data and advanced computational fluid dynamic modeling; (2) technologies for co-feeding coal and alternative feedstocks to high pressure gasifiers; (3) instrumentation for real-time measurement of critical process conditions; and (4) corrosion resistant refractories for harsh slagging gasifier and alternate feedstock operating environments. Products from the instrumentation and refractory development are to be evaluated at CCT projects demonstrating IGCC.

Industry efforts, through the PSDF, support development of a fuel-flexible feed system capable of handling biomass, and wastes from refinery, municipal, industrial, agricultural, and forestry activities.

Milestones include: (1) demonstration of a fuel-flexible feed system by 2006, and (2) commercial designs for a gasification-based power system having greater than 52 percent efficiency (HHV), SO_2 and NO_x emissions at or below 0.06 lb/10^6 Btu, particulate matter emissions at or below 0.003 lb/10^6 Btu, and capital costs less than $1,000/kW.

Gas cleaning and conditioning activities support development of particulate and chemical contaminant gas cleanup technologies necessary to achieve Vision 21 efficiency and emissions goals. This requires systems capable of operating in gasifier environments, and providing the downstream gas quality needed for integration with fuel cells, advanced turbines, and synthesis gas conversion technologies. HGPF and MCF research under the PFBC program area is leveraged by ensuring that gasifier requirements are met along with those of PFBC. In addition, hot gas cleanup using regenerable sorbents is being addressed, with current emphasis on a transport desulfurization reactor and associated attrition-resistant sorbent and reactor model development. Other novel concepts are under study, the most promising of which will undergo testing at NETL's GPDU, and if successful, subsequently at the PSDF.

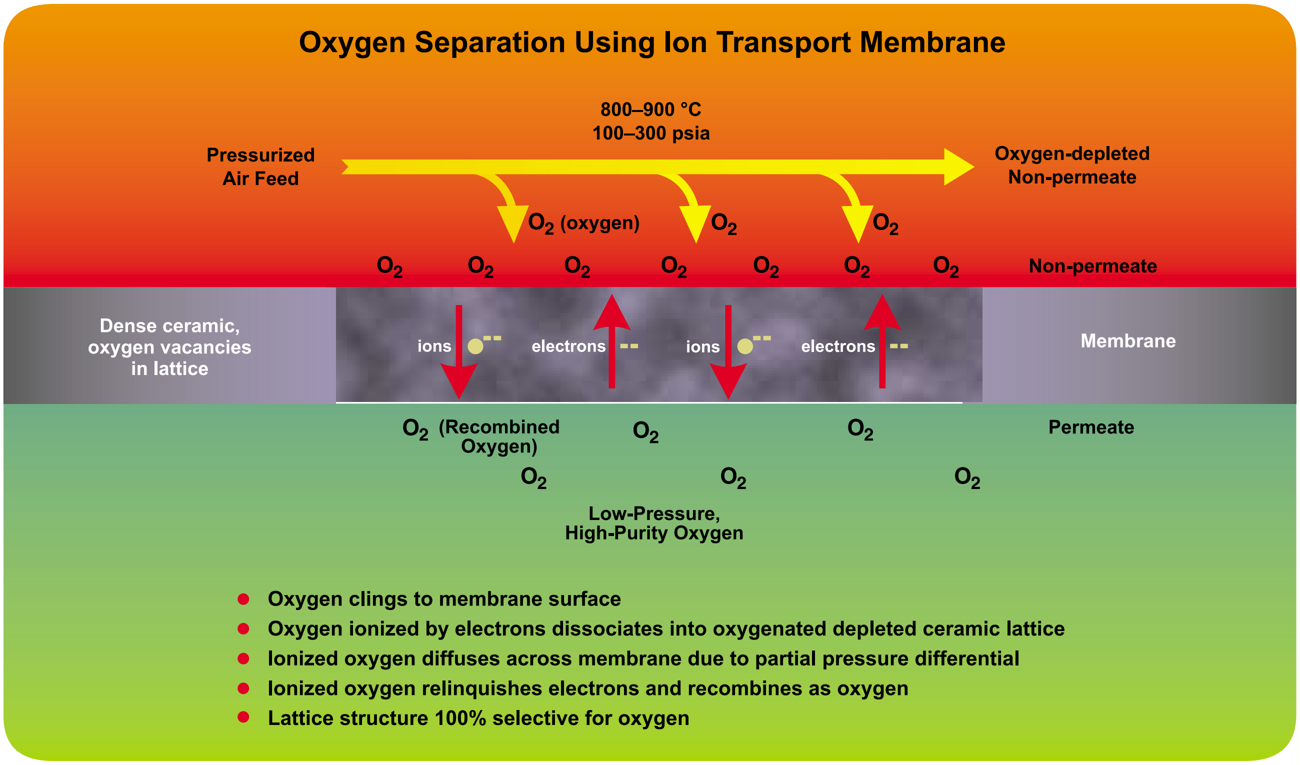
Plans are to complete development of ceramic and metallic candle filter-based HGPF systems (filter elements, failsafes, and support system) by 2002. Research on alternate HGPF materials and configurations will proceed in parallel resulting in pilot-scale tests of advanced HGPF designs (ceramics for combustion and metallic for gasification) in 2004.

MCF concepts addressing gas phase chemical contaminants, solicited in 2001, will be integrated with advanced HGPF systems in 2005. In 2006, pilot-scale tests of an MCF/HGPF barrier filter system will be conducted.

Gas separation activities are focused on development of a new breed of technologies using membranes and other novel approaches to dramatically reduce the energy required for gas separations critical to achieving Vision 21 goals. Two of the largest gas producing companies in the United states — Air Products and Chemicals, and Praxair — are developing ionic transport membranes (ITMs) for separating oxygen from air. These ITMs will displace energy-intensive cryogenic air separation plants, which represent a major cost for current gasification technologies. The Oak Ridge and Argonne National Laboratories are taking the lead in development of hydrogen separation membranes, which will reduce the cost of fuel cell applications and open the door to a hydrogen economy. Development of CO_2 separation technologies is also underway, including membrane and CO_2 hydrate separation techniques, through the combined efforts of industry, academia, and National Laboratories. CO_2 separation enables sequestration and hydrogen separation from gasifier-derived syngas.

Milestones include: (1) commercial availability of ITM/oxygen separation technology by 2008; (2) commercial offering of ceramic hydrogen separation membrane technology by 2010; and (3) commercial designs for a CO_2 hydrate separation technology by 2011.

Products/by-products activities are aimed at producing value-added products in lieu of waste streams to improve gasification technology economics. Efforts are ongoing to improve the quality and marketability of ash and slag derived from CCT projects demonstrating IGCC, and to evaluate a single step sulfur removal process at the PSDF.



PROGRAM AREAS

Systems Analysis/ Product Integration

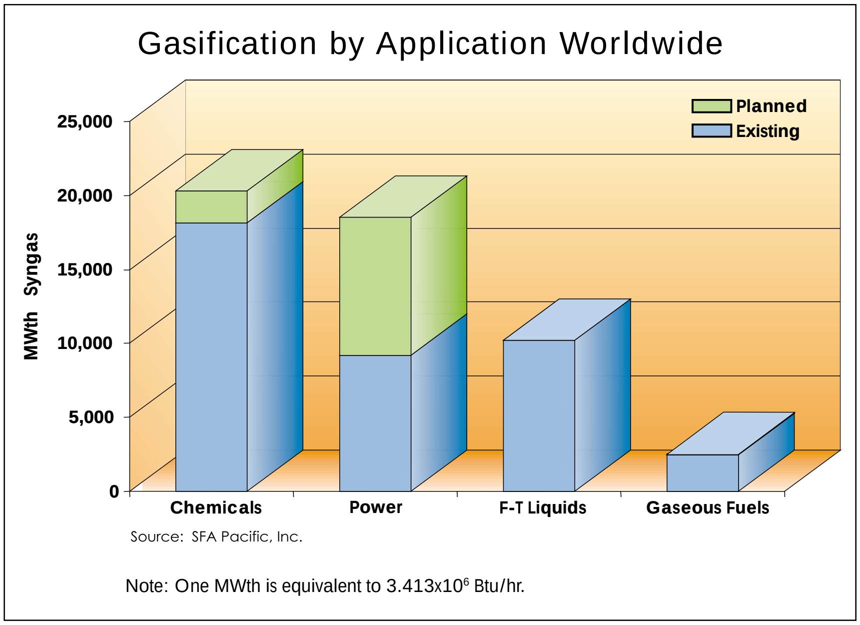
Process engineering and analyses are carried out by DOE's Gasification Product Team composed of Headquarters and NETL personnel. These activities provide the studies necessary to guide future R&D efforts, define R&D initiatives, and support domestic and international commercialization activities. Process optimization studies are being pursued to determine the lowest cost and highest efficiency approaches for baseload, co-generation, and co-production applications. Similar studies also will be pursued for advanced configurations that incorporate fuel cells and CO_2 capture technologies. Life cycle analyses are being performed to evaluate cradle-to-grave performance.

Technology demonstration is also supported by DOE. Demonstrations include CCT program demonstrations of four IGCC technologies using different gasifiers and gas cleanup systems. DOE ensures that important cost and performance data is collected and disseminated to support market acceptance of the technologies. Also, the data collected and the lessons learned are used to build a foundation for a next generation of gasification technologies.

Moreover, the Gasification Technologies program is embarking on projects that will lead to the demonstration of co-production technologies for the manufacture of electricity, fuels, and chemicals; and the application of gasification in the pulp and paper industry.

The market potential for gasification-based processes is expected to grow considerably in the next few decades because of gasification's environmental performance and operational flexibility. Databases on existing and planned gasification-based projects have been developed and are continually being updated. This information will be used to develop market strategies for both domestic and international markets.

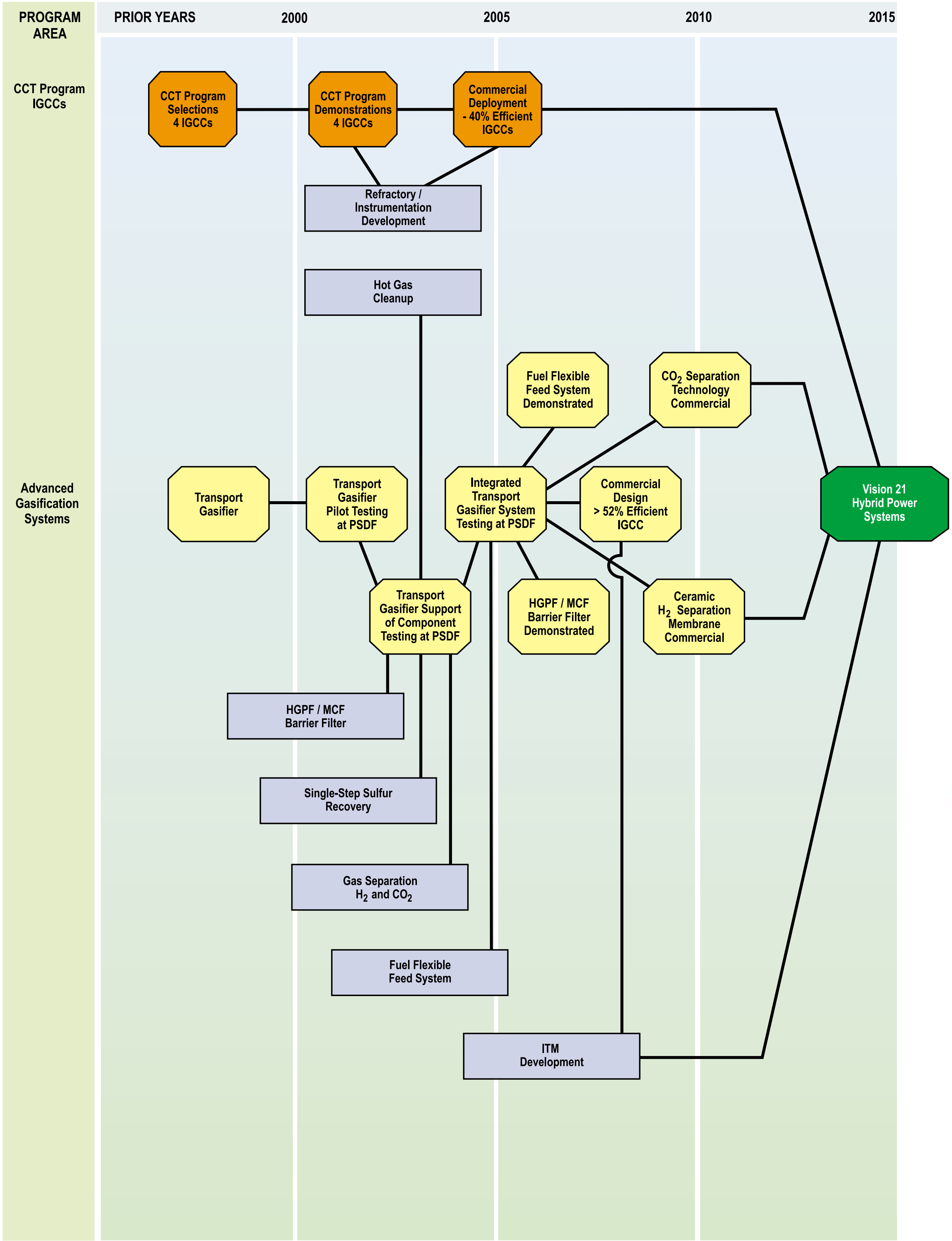
The following roadmap summarizes activities under the Gasification Technologies program area.



A recent surge in gasification-based technology applications has raised existing capacity to around 40,000 MWth (a measure of syngas heat energy). Much of the movement has been in the power industry.

PROGRAM AREAS

Roadmap


PROGRAM AREA
PRIOR YEARS
2000
2005
2010
2015
CCT Program IGCCs
CCT Program Selections 4 IGCCs
CCT Program Demonstrations 4 IGCCs
Commercial Deployment - 40% Efficient IGCCs
Refractory / Instrumentation Development
Hot Gas Cleanup
Advanced Gasification Systems
Fuel Flexible Feed System Demonstrated
CO_2 Separation Technology Commercial
Transport Gasifier
Transport Gasifier Pilot Testing at PSDF
Integrated Transport Gasifier System Testing at PSDF
Commercial Design > 52% Efficient IGCC
Vision 21 Hybrid Power Systems
Transport Gasifier Support of Component Testing at PSDF
HGPF / MCF Barrier Filter Demonstrated
Ceramic H_2 Separation Membrane Commercial
HGPF / MCF Barrier Filter
Single-Step Sulfur Recovery
Gas Separation H_2 and CO_2
Fuel Flexible Feed System
ITM Development

Advanced Turbine Systems

Performance Targets

Size: Utility-Scale

Efficiency: >60% LHV

NO_x Emissions: <9 ppm

Cost of Electricity:
10% reduction

Year: 2002

A gas turbine produces a high-temperature, high-pressure gas working fluid to induce shaft rotation by impingement of the gas upon a series of specially designed blades. The shaft rotation drives an electric generator and a compressor for the air used by the gas turbine. Many turbines also use a heat exchanger called a recuperator to impart turbine exhaust heat into the combustor's air/fuel mixture.

The gas turbine, once used solely in aviation applications, has evolved into a workhorse in industry and has become the premier electric generation system for peak and intermediate loads. Gas turbines are compact, lightweight, easy to operate, and come in sizes ranging from several hundred kilowatts to hundreds of megawatts.

The Advanced Turbine System (ATS) effort, in support of central power systems, is seeking to enhance the efficiency and environmental performance of utility-scale gas turbines. The utility-scale ATS objectives for operation on natural gas are to achieve 60 percent efficiency or more in a combined-cycle mode, NO_x emission levels less than 9 ppm, and a 10 percent reduction in the cost of electricity. Significantly higher turbine inlet temperatures are required in order to achieve the efficiency objective. These higher temperatures in turn require advancements in materials, cooling systems, and low-NO_x combustion techniques.

The utility-scale ATS program is being carried out along parallel paths: (1) major systems development; and (2) technology base development, which supports ongoing and future major systems development. General Electric and Siemens Westinghouse, world renowned turbine manufacturers, are conducting the major systems development work. Each is developing their own concept under separate cost-shared cooperative agreements with DOE. Both companies have completed component and subsystem testing. Completion of prototype system testing to evaluate combustion, heat transfer, and aerodynamic design under actual operating conditions is scheduled for 2001. Commercial units are scheduled for market entry in 2002, to meet increasing demands for natural gas-based power.

The focus of General Electric's effort is an "H" series gas turbine. To accommodate elevated turbine inlet temperatures, General Electric is employing a novel steam cooling system and newly developed single-crystal turbine blades. Development of the single-crystal casting technique for large complex components represents a breakthrough in manufacturing methods. Single-crystal materials are stronger than polycrystalline materials and provide superior resistance to high-temperature corrosive conditions.

Siemens Westinghouse is using its 501G turbine as a test bed for the ATS design. Computer modeling has allowed design refinements that are contributing to capital cost re-

General Electric's utility-scale advanced turbine

Siemens Westinghouse house utility-scale advanced turbine

duction and efficiency enhancement. These include lean, premixed combustion and catalytic systems. Siemens Westinghouse also has developed brush and abradable coating seals to reduce internal leakage, and thermal barrier coatings for turbine blades to permit higher temperatures. These developments have already been incorporated into the commercial 501G turbine.

The ATS technology base development effort includes both the advancements in materials, cooling, instrumentation, and control and combustion techniques needed for operation at elevated temperatures, as well as specific studies in support of component and systems development in areas such as heat transfer and aerodynamics. The work is carried out through in-house research at NETL and an industry/university consortium established under the ATS program.

NETL conducts collaborative research with universities and industry in low-emissions and low-Btu combustion at highly instrumented, established facilities. The low-emissions activities support ATS NO_x emission reduction goals. The low-Btu combustion work supports expanding the fuel flexibility of gas turbines by developing the capability to operate on gases derived from gasification of coal, biomass, and wastes. The in-house work also involves development of the associated instrumentation and controls. An example of a specific NETL activity is its partnership with United Technology Research Center. The work entails identifying and modeling combustor configurations to efficiently burn high-moisture, high-pressure gas/air mixtures. This humid air turbine (HAT) concept has the potential for very low emissions and enhanced power and efficiency.

The industry/university consortium supports applied research for 100 U.S. universities, including workshops and student internships at industry facilities. Under the direction of the South Carolina Institute for Energy Studies, contracted universities perform applied research specific to the needs of the ATS developers in combustion, aerodynamics, materials, and heat transfer.

NEXT GENERATION TURBINES

Performance Targets

Flexible Turbine Systems:
15% net efficiency gain

Turbine/fuel cell hybrid:
70% efficiency mid-term
80% efficiency long-term

A follow-on program to the ATS is the Next Generation Turbine (NGT) program. The NGT goals are to:

- Reduce the life-cycle cost and improve the RAM of the existing and future turbine power plant infrastructure;
- Develop and demonstrate ultra-clean, high performance turbine power systems for near-term power markets and long-term integration into Vision 21 power plants;
- Develop advanced materials, combustion systems, computational tools, and sensors/controls/instrumentation to solve crosscutting technical barriers; and
- Collaborate with regulatory agencies and develop sound technical information to produce appropriate and beneficial regulatory decisions related to gas turbine power plants.

NGT systems will provide significant public benefits through increased reliability, superior performance, reduced life-cycle costs, and near- and long-term reductions of CO_2, NO_x, and other emissions. Because NGT systems will be fuel-flexible, they will expand the options for high-efficiency conversion of domestic fuels into electric power.

In the near term, NGT systems will be suitable for new capacity, repowering of older fossil units, combined heat and power applications, and as efficiency enhancement units for existing fossil-fueled steam plants. In the long term, NGT systems will be adapted and integrated into Vision 21 fossil-fueled plants.

Enabling technologies developed under the program may benefit and support other missions of the U.S. government, such as enhancing defense capability and serving the needs of future-generation military operations. Another large benefit of the NGT program is the creation and maintenance of U.S. jobs directly related to the manufacture of turbine systems, and those indirectly created and maintained because of the low-cost, environmentally superior performance that will result, helping to keep U.S. businesses competitive.

The NGT program intends to establish a committee to coordinate activities with members from the DOE Office of Energy Efficiency and Renewable Energy (EERE), National Aeronautics and Space Administration (NASA) , Department of Defense (DoD), National Association of State Energy Officials, California Energy Commission, National Institute for Standards and Testing, and other federal and state organizations. Specific linkages include: the EERE micro-turbine program: NASA Ultra-Efficient Engine Technology program, and DoD propulsion programs — Integrated High Performance Turbine Engine Technology, the Versatile, Affordable Advanced Turbine Engines program, and the Navy Future Ships programs. In addition, an Industry Peer Review Board is being established to ensure program quality and relevance; and workshops and planning meetings will be held throughout program implementation to seek stakeholder input.

There are three elements of the NGT program — Systems Development and Integration, RAM Improvement, and Crosscutting Research and Development.

Systems Development and Integration

Turbine systems will be developed to meet the needs of emerging deregulated power supply markets. These systems will respond to stakeholder needs by providing highly efficient, reliable, and ultra-clean performance, and by offering flexibility to perform effectively independent of duty cycle or fuel used. Systems currently under evaluation and development are flexible turbine systems and turbine/fuel cell hybrids greater than 30 MW in output rating.

Six companies have been selected by DOE to define **Flexible Turbine Systems:**

- *Pratt and Whitney,* will conduct a study of an intercooled aero-derivative industrial gas turbine that is based on a commercial aircraft engine (PW8160) now being developed.
- *Rolls Royce Allison,* will enhance and simplify a gas turbine engine design now used in U.S. Navy ships (WR21) by modifying recuperation and intercooling technologies.
- *Siemens Westinghouse Power Corp.,* will pursue a modular gas turbine with new "enabling" technologies in a single, low-cost system design that holds worldwide applications.
- *GE Power Systems,* will recommend an engine configuration after performing a parametric study of three broad categories of gas turbines: aero-derivative, heavy duty, and a potential hybrid combining components of the other two categories.
- *Ramgen Power Systems, Inc.* is using established ramjet principles applied in missiles and military aircraft in the develop-ment of a stationary power generator. Aerodynamics at supersonic velocities are applied to compress and expand a working fluid in lieu of mechanical parts, thereby simplifying design and enabling low capital costs. Moreover, complete pre-combustion fuel mixing and high fuel conversion efficiency enable simple cycle efficiencies greater than 50 percent, use of dilute waste fuels, and NO_x emissions below 4 ppm.

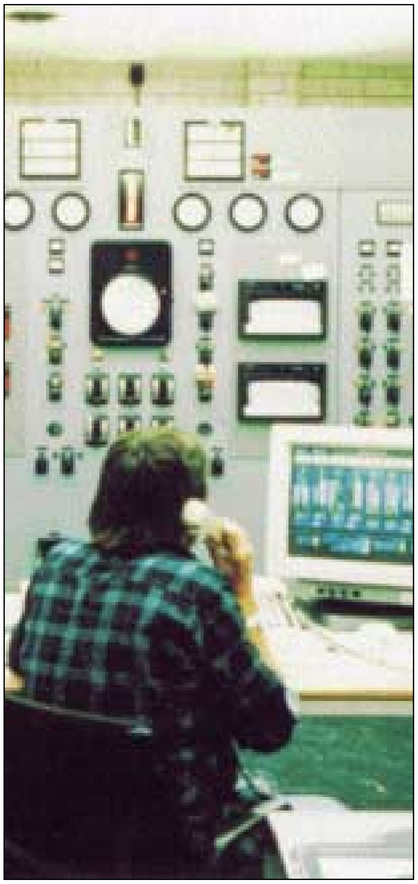
  Under a partnership with NETL, Ramgen Power Systems, Inc. is now testing a pre-prototype (beta) Ramgen engine. Work will commence on the manufacture of a second smaller scale beta engine in 2001 for field testing. Longer-term development plans are to build a Mach 3.25 unit with a simple cycle efficiency of approximately 44 percent and to ultimately build a Mach 3.5 unit with an initial cycle efficiency of 50 percent, and eventually 55 percent as materials and cooling systems improve. The size range envisioned is 500 kW to 40 MW.
- *Clean Energy Systems* is using a process that injects water into a reactor where oxygen (in lieu of air) is used to combust natural gas. The resultant gas, which is 95 percent steam and 5 percent carbon dioxide, is used to drive steam turbines at pressures of 3,000 pounds per square inch, or more, and at temperatures of 2,600–3,200 °F. The high temperatures and pressures produce efficient performance, no combustion products are released to the atmosphere, and CO_2 can be effectively separated for sequestration.

  NETL is partnering with Clean Energy Systems to fabricate and demonstrate a 10-MW gas generator by 2002. Ultimately, if successful, the system will be integrated into a Vision 21 power plant concept.

Promising concepts could become the basis for more detailed engineering designs, component development and testing, and ultimately, the manufacturing of prototype machines. If the development effort is successful, the first NGT turbine systems could be ready for market entry around 2008. Integration of NGT technology into Vision 21 plants is planned for the 2010–2015 time frame.

Turbine/Fuel Cell Hybrids use synergistic integration of high-temperature fuel cells and gas turbines. The goals for these hybrids are to achieve 60 percent efficiency in the near term, 70 percent in the midterm, and 80 percent in the long term (lower heating value) at costs 10–20 percent lower than comparably sized conventional power plants.

Hybrid systems studies by Siemens Westinghouse Power Corp., Rolls Royce Allison, FuelCell Energy, Caterpillar, and Northern Research and Engineering Corporation laid the foundation for follow-on efforts. DOE selected FuelCell Energy-Capstone Turbine and Rolls Royce Allison to conduct 280-kW hybrid demonstrations and develop designs for a 40-MW hybrid system. DOE also has agreements with Siemens Westinghouse to conduct hybrid demonstrations at 250-kW and 1-MW scales. EPA and the European Commission are to partner with DOE on the demonstrations.



RAM Improvement

Reliability, Availability, and Maintainability (RAM) Improvement efforts will develop the instrumentation, inspection and examination technology, analytical modeling, and evaluation techniques necessary to monitor turbine performance and determine when maintenance is needed based on turbine condition. Plant operations technologies will be integrated into advanced information platforms for multi-facility management. The power industry is moving toward managing plant maintenance through condition-based monitoring and expert health prediction tools. The introduction of increasingly high turbine temperatures requires close operational surveillance of critical hot-gas-path components, which in turn requires development of predictive models and instrumentation to assess their integrity.

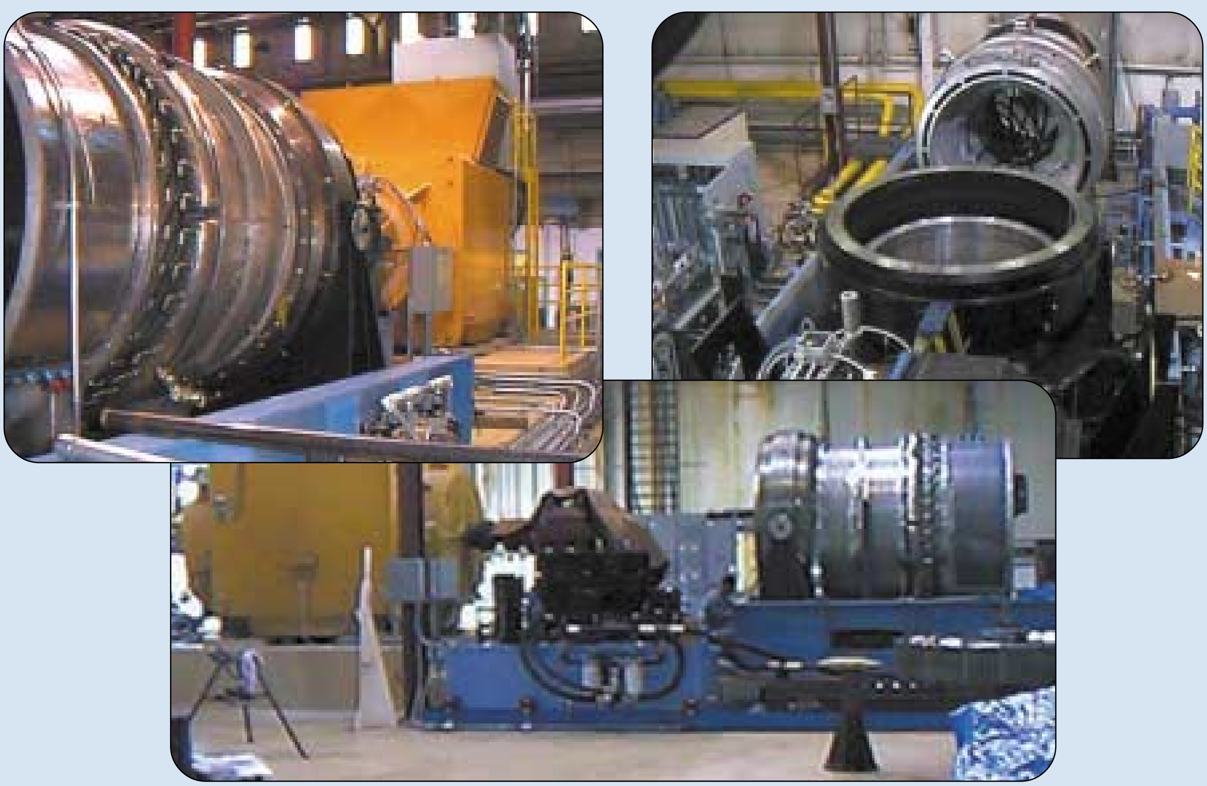
RAM Improvement activities will be implemented by a consortia consisting of government organizations, industry, universities, and National Laboratories.

Crosscutting Research and Development

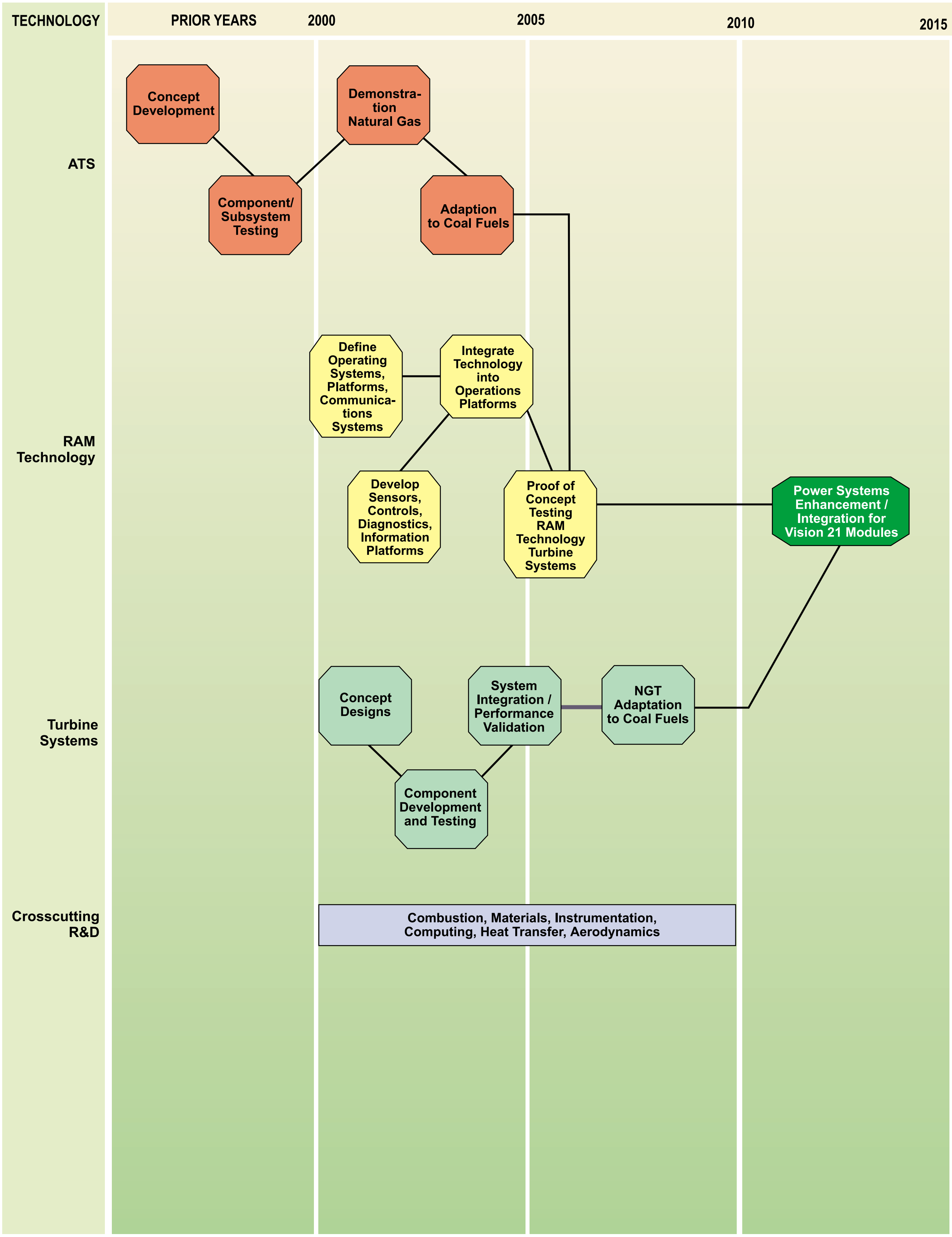
Crosscutting Research and Development provides the combustion modeling, materials science, computer simulations, and instrumentation needed to support new technology development. Activities will be conducted by a consortia of U.S. government organizations, industries, universities, and National Laboratories.

The following roadmap summarizes activities under the two Turbine Systems program areas.

Ramgen Engine Prototype



Roadmap


TECHNOLOGY
PRIOR YEARS
2000
2005
2010
2015
ATS
Concept Development
Component/ Subsystem Testing
Demonstration Natural Gas
Adaption to Coal Fuels
RAM Technology
Define Operating Systems, Platforms, Communications Systems
Integrate Technology into Operations Platforms
Develop Sensors, Controls, Diagnostics, Information Platforms
Proof of Concept Testing RAM Technology Turbine Systems
Power Systems Enhancement / Integration for Vision 21 Modules
Turbine Systems
Concept Designs
Component Development and Testing
System Integration / Performance Validation
NGT Adaptation to Coal Fuels
Crosscutting R&D
Combustion, Materials, Instrumentation, Computing, Heat Transfer, Aerodynamics

In Partnership with Industry

Tampa Electric Company

In 1989, Tampa Electric Company embarked on a mission to respond to customer needs for additional power in the most fiscally and environmentally responsible manner possible. Tampa Electric first engaged environmental groups to identify a plant location that represented the least threat to the environment. A consensus was reached on an abandoned phosphate mine site in Polk County, Florida. Coal was chosen as the fuel to keep operating costs low, and IGCC technology was selected to provide the least environmental impact.

Tampa Electric Company's collaboration with environmental groups resulted in the creation of uplands, wetlands, and a wildlife corridor.

In 1996, the 250-MWe IGCC Polk Power Station, Unit No. 1 went on line and continues in commercial service. The heart of the unit is a Texaco oxygen-blown, entrained flow gasifier. As of September 2000, the IGCC system had accumulated over 18,000 hours of operation and produced over 7,000,000 MWh of electricity.

The project has drawn visitors from around the world, and the Texaco gasifier-based IGCC is realizing a significant number of commercial sales.

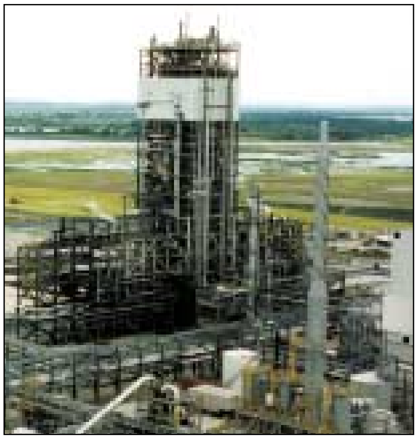
For its accomplishments, the project is the recipient of *Power* magazine's 1997 Powerplant Award, the 1993 Ecological Society of America Corporate Award, the 1993 Timer Powers Conflict Resolution Award, and the 1991 Florida Audubon Society Corporate Award.

General Electric's H System™ Turbine

In September 1999, General Electric announced that its newest H System™ gas turbine was ready to move over the commercial threshold. Having passed a critical verification test, the H System™ gas turbine will be sited at Sithe's Heritage Station in Scriba, New York. This turbine is a culminating achievement of the DOE's Advanced Turbine System research and development program that began in the early 1990s, when General Electric was one of six developers selected to begin designing concepts for a breakthrough turbine system.

Designed to work in a combined-cycle mode, the H System™ gas turbine will be the first to break through the 60 percent efficiency threshold, beating the efficiency of prior best available turbines by five percentage points. This significant jump in efficiency makes the H System™ turbine the lowest producer of carbon dioxide per kilowatt of electricity of any gas turbine available today.

Moreover, the H System™ turbine operates cleaner than any of today's utility gas turbines. Its NO_x emission levels of 9 ppm will be half the average of the turbines now in use, making the new technology suitable for siting in the Nation's most environmentally sensitive areas.



Tampa Electric Company's 250-MWe Polk Power Station, Unit 1 IGCC facility

The 400-ton Model MS7001H (H System™) turbine is the size of a locomotive